Chapter 2
Energy

Fire is the basis of all craft.
Without it, Man could not persist.

Hesiod, 700 BC

2.1 Understanding the Prime Mover

Energy is the capacity to cause changes in the world; it is stored in matter and force fields. Energy conversion provides the work that drives the processes of life and the production of goods and services.

Energy lets the Sun shine, the rain fall, and the wind blow. It surrounds us as light and heat. It penetrates us and keeps us alive as food. If hard work drains us of too much energy, we collapse. Energy moves masses in construction, when dredgers dig and cranes heave, and deals blows of destruction when storms rage, lightning strikes, and the Earth quakes. It transmits information imprinted upon sound and electromagnetic waves. Liberated by the combustion of chemical fuels, and in nuclear reactions, it moves vehicles, ships, planes, and rockets and performs more physical work in the machines of our factories than all humans on Earth could supply. And yet, science got a clear concept of energy only in the nineteenth century. And energy's significance is hidden to economic theory even these days.

2.1.1 How the Energy Concept Evolved

The problem with understanding energy is that we do not perceive it in a unique way. Rather, it stimulates our senses and contacts with the outside world in many different and seemingly incoherent ways. Energy is present in so many different forms, such as light, fire, flowing water, wind, wood, wheat, meat, gunpowder, coal, mineral oil, and natural gas that for a long time people did not realize what they have in common. Sometimes energy carriers also serve different purposes, which also

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creates confusion. For instance, many economic production processes are powered by the burning of mineral oil. Besides, a small share of oil also serves as a lubricant. Thus, people often call oil "the lubricant of the economy," camouflaging its real role as the still most important *fuel* of the economy.

The following short tale of energetics is based on the treatise *Die Energie* [1], written by the 1909 Nobel laureate in chemistry *Wilhelm Ostwald* (1853–1932). It shows how in the course of history some of the brightest minds have struggled to penetrate the essence of what we now call energy, and that they finally succeeded with the help of experiments and mathematical analysis.

The Greek philosopher and scientist *Aristotle* (384–322 BC), starting from equilibrium considerations for balances, thought about levers and the motion of their ends when different weights act on lever arms of different lengths. He used the Greek word *energeia*, but the meaning remained vague.

The situation stayed this way for nearly 2,000 years until, at the end of the Middle Ages, inquisitive minds turned their attention away from philosophical and theological speculations to asking nature experimental questions.

Galileo Galilei (1564–1642) showed that there is equilibrium on an inclined plane, and in other simple machines of that time, when the center of mass of all movable masses neither goes up nor goes down. His pupil Torricelli added the remark that in stable equilibrium the center of all masses assumes the lowest position. Investigating the free fall of bodies, Galileo found that their velocity is independent of the body mass and increases linearly with time. Experimental observations were the basis of all his theoretical reasoning. This made Galileo the founder of modern science. He stated that the book of nature is written in mathematical symbols.

Isaac Newton (1646–1727) published his *Philosophiae naturalis principia mathematica* in 1687. In this work Keppler's laws for the motion of the planets are derived from Newton's law of gravitation. This breakthrough, Newton's axioms of mechanics, and calculus (invented independently by Newton and Leibniz) became the foundations of classical theoretical physics. But energy was not yet an issue.

In 1717 *Jean Bernoulli* (1667–1748) wrote in a letter to Verignan: "En tout équilibre de forces quelconques, en quelque manière qu'elles soient appliquées, et suivant quelques directions qu'elles agissent les uns sur les autres, ou médiatement, ou immediatément, la somme de énergies affirmatives sera égale à la somme des énergies négatives, prises affirmativement." ("In every equilibrium of whatsoever forces, no matter how they are applied and under what angles they act directly or indirectly relative to each other, the sum of the positive energies is equal to the positively taken sum of the negative energies.") "Energy" is explicitly defined as the product of force times the (virtual) way in its direction. Further elaborations on the "principle of virtual works (or displacements)" resulted in the basic equations of statics. They are all based on the experience that it has never been possible to build a perpetual motion machine, i.e., a machine that creates work out of nothing, where work is the sum of all products of force times the parallel (positive) and antiparallel (negative) parts of way elements along which the force acts.

On the basis of observations such as those of a swinging pendulum, *Gottfried Wilhelm Leibniz* (1646–1716) reasoned that there should be an invariant whenever work is consumed in a machine, in order to produce velocities of moving masses. This invariant was recognized as the sum of all work performed and of "all living forces," as Leibniz called what later was given the name "kinetic energy" by *William Rankine*.

After this discovery of what is now known as the conservation law of mechanical energy, the concept of "energy" was used as a popular name for the "living force" by *Thomas Young* (1773–1829) at the beginning of the nineteenth century. *William Thomson* (1824–1907) later Lord Kelvin, firmly introduced the energy concept in science and emphasized that every state of a body is characterized by a well-defined energy value, its eigenenergy.

The decisive steps that extended the law of energy conservation beyond the realm of mechanics, and revealed energy as the fundamental constituency of the world besides matter, were taken by the physician *Julius Robert Mayer* (1814–1878) and the brewery owner and private scholar *James Prescott Joule* (1818–1889).

The story of Mayer's discovery deserves to be told in some more detail, because it shows how an outsider achieved a breakthrough and how difficult it was for him to communicate it to the scientific community.

Mayer, as a ship physician on a Dutch sailing ship that sailed to the West Indies, observed during occasional bleeding of the crew that after arrival of the ship in the tropics, the blood came out of the veins much redder than in colder latitudes. He concluded that in the warmer environment the body has to produce less heat by the physiological combustion of food in order to maintain constant temperature, so vein blood contains more unused oxygen, which causes the redder color. This conclusion was near at hand, because *Antoine Laurent de Lavoisier* (1743–1794) had shown that the warmth of human and animal bodies is indeed due to food combustion. In his youth, Mayer had tried to build a perpetual motion machine. In a more mature way, he now rethought the issue of work. The human body can perform work and produces heat. Is there a relation between the two? In trying to find the answer, he was handicapped by his lack of formal training in physics. On the other hand, he was neither handicapped by traditional scientific thinking habits nor afraid to wonder whether mechanical work and heat, two seemingly so different things, are manifestations of one and the same entity. But when he tried to put his thoughts into a mathematical-physical form, nobody understood them at first. A paper he sent to the *Annalen der Physik* in 1841, and subsequent inquiries about its fate, were simply ignored by the editor Poggendorf. Mayer was more successful with his second attempt. The article entitled "Bemerkungen über die Kräfte der unbelebten Natur" ("Remarks on the forces of inanimate nature"), written at the beginning of 1842, was soon published by the *Annalen der Pharmacie und Chemie*. One of the editors of this journal, *Justus Liebig*, had thought himself about the utilization of food in animal bodies, which was the starting problem of Mayer's considerations. The article cut its way through conceptual jungles. It talked of "forces" when "energy" was meant. In the introduction Mayer said that hitherto "force" was the concept of an unknown, impenetrable, hypothetical entity and that his article tried

to contribute to clarification. Observations guided the way. For instance, Mayer pointed out that often a motion stops without inducing another motion or lifting a weight. He stated that an existing “force” cannot vanish but can only change into another form and asked what other form might be taken by the “force” that is the sum of motion and the “falling force” (*Fallkraft*). He noted that by shaking water sufficiently intensely, one can enhance the water temperature from 12°C to 13°C and raised the question of where the corresponding heat comes from. Mayer recalled the inverse process in the steam engine, which “decomposes” heat into motion and the lifting of weights. Finally, he reported his discovery of the mechanical heat equivalent with the following words: “…es ergibt sich …dass dem Herabsinken eines Gewichtsteils von einer Höhe von zirka 365 m die Erwärmung eines gleichen Gewichtsteils Wasser von 0° auf 1° entspreche.” (“ …one finds …that the sinking of one weight unit from a height of about 365 m corresponds to the heating up of the same weight unit of water from 0° to 1°.”) Although Mayer’s heat equivalent is by a factor of 0.85 smaller than that in later textbooks, he was the first to state clearly that heat and mechanical work are two forms of the same thing and to establish their quantitative relation nearly correctly. In 1845 he published the article entitled “Über die organische Bewegung und den Stoffwechsel” (“On organic motion and metabolism”), where he stated the law of energy conservation more generally.

Independently from Mayer and only a little later, Joule arrived at the same conclusions in a completely different way. The revenues from his Manchester brewery enabled him to follow his scientific interests. Electromagnetism fascinated him, because he expected to gain cheap work from the attractive forces exerted by an iron core encircled by electric currents. He investigated all different factors that are relevant for the operation of electric machines. (In so doing, he found a number of important physics laws. In cooperation with William Thomson he discovered the Joule–Thomson effect, which is the basis for the liquefaction of gases.) He observed that the heat developed in the current-conducting wires – this heat was later given Joule’s name – was uniquely related to the consumption of chemicals in his galvanic elements. Furthermore, he found that the currents in the wires of a machine produce less heat when the machine works than when the machine stands still, all other factors being equal. His starting point was similar to Mayer’s. The animal organism is only replaced by the electromagnetic apparatus and its galvanic elements. In both cases chemical reactions are the source of mechanical work and, more or less, heat. The situation was rather complicated, and Joule tried to simplify it. He asked himself: How can the simplest relation between work and heat be established? He answered: When work is changed into heat by friction. If the idea is correct that work and heat are equivalent, then a given amount of work must always produce the same amount of heat, independently of the special ways in which one may convert work to heat. Joule performed experiments in which the work of falling weights was converted to heat in many different ways and concluded that there is indeed an invariant relation between work and heat. The corresponding communication was published in 1843, just one year after Mayer’s first article.

Subsequently, the physiologist and physicist *Hermann Helmholtz* (1821–1882) deepened the understanding of the principle of energy conservation mathematically

and in many details. Still, he used the name *Kraft* ("force") for what is energy. When *James Clerk Maxwell* (1831–1879) developed his theory of electromagnetism between 1861 and 1864, electromagnetic energy was readily included in the general concept of energy.

With that the beautiful structure of classical physics was firmly established. Physicists believed that their deterministic laws would, in principle, allow them to predict the evolution of everything, from the beginning of the universe to its end.

At the start of the twentieth century, more than 2,300 years after Aristotle had talked about *energeia* in the context of natural phenomena, the overwhelming importance of "energy" for a proper understanding of the world had been realized by all natural scientists. For instance, Ostwald wrote in [1]: "Will sich heute ein Physiker oder Chemiker recht fortschrittlich gebärden, …so …definiert [er] die Naturwissenschaft als die Lehre von der Umwandlung der beiden unzerstörlichen Dinge, der Materie und der Energie…" ("If a physicist or chemist wants to show himself really progressive these days …he defines natural science as the science of the conversion of the two indestructible things, matter and energy …"). And he predicted: "…der Begriff der Materie [wird] als ein untergeordneter …sich herausstellen …" ("…the concept of matter will turn out to be secondary").

Between 1948 and 1978 the International Union of Pure and Applied Physics developed and recommended the International System of Units, abbreviated by *SI system*. The basic SI units and the derived SI units relevant for the measurement of energy are:

> meter (m) for distance, second (s) for time, kilogram (kg) for mass, ampere (A) for current, kelvin (K) for absolute temperature. newton (N) for force ($1\,\mathrm{N} = 1\,\mathrm{m\,kg/s^2}$), joule (J) for energy ($1\,\mathrm{J} = 1\,\mathrm{m^2kg/s^2} = 1\,\mathrm{N\,m}$), and watt (W) for power ($1\,\mathrm{W} = 1\,\mathrm{m^2\,kg/s^3} = 1\,\mathrm{J/s}$).
> One energy unit that often appears on energy bills is the kilowatt-hour (kWh); $1\,\mathrm{kWh} = 3.6\times10^6\,\mathrm{J}$.

2.1.2 Energy for All and Forever

Ostwald's prediction that the concept of energy will dominate physics was proven right by the deepening understanding of the energy–matter world during the twentieth century. *Albert Einstein's* special theory of relativity showed the equivalence of energy and mass in 1905. This later explained the liberation of energy in nuclear fission and fusion. And according to the present theory of cosmic evolution, all matter has condensed out of the primordial Big Bang energy in a series of phase transitions.

Einstein discovered that energy E and mass m are equivalent, when he realized that classical Newtonian mechanics must be augmented to account for experimental observations such as those of *Albert A. Michelson*, according to which all observers measure the same speed of light in a vacuum, which is $c = 299,792\,\text{km/s}$, no matter how fast they move at constant velocity relative to each other and to the source of light. The equivalence relation is[1]

$$E = mc^2. \tag{2.1}$$

Energy was also the key that opened the door to quantum mechanics, which shattered the foundations of classical physics. This happened between 1900 and 1930. Among the pioneers were the Nobel laureates in physics *Max Planck, Albert Einstein, Niels Bohr, Werner Heisenberg, Erwin Schrödinger*, *Paul Dirac*, *Wolfgang Pauli*, and *Max Born*. They discovered that experimentally observed phenomena such as the radiation emitted by black bodies, the emission of electrons by illuminated metal surfaces (photoelectric effect), and all processes in the microworld of atoms can only be understood if one assumes that energy is quantized in the sense that atoms emit electromagnetic radiation of frequency f in energy packets (photons) of size hf, where $h = 6.625 \times 10^{-34}$ W s^2 is Planck's constant. The reason is that atoms can accommodate their electrons only in discrete (quantized) energy levels, between which the electrons jump down or up if they emit or absorb energy. This contradicts a fundamental conviction of classical physics, expressed by the old saying *natura non fecit saltus* (nature does not make jumps). Quantum mechanical computation of the atomic energy levels requires knowledge of the classical energy function, called a *Hamiltonian*, for the atomic system. (Ironically, neoclassical economics, which has little room for energy, has borrowed the mathematical formalism of Hamiltonians from classical mechanics.) In quantum mechanics the Hamiltonian is usually the sum of kinetic and potential energies. An example is given by (2.27) in Appendix 1 of Chap. 2. Replacing these energies by operators that operate on quantum mechanical states, one can calculate all physical properties of atomic systems in full agreement with experiment. However, quantum mechanics allows only predictions of *probabilities* for properties and processes in the microworld of atoms. These probabilities can also affect the macroworld

[1] If m is the mass m_0 of a body at rest relative to an observer, this relation gives the amount of energy the observer would obtain from nuclear reactions that convert all of m_0 into energy. Similarly, if an electron and its antiparticle, the positron, meet, they annihilate and turn into photons, the quanta of electromagnetic radiation, whose energy is given by (2.1), m being the sum of the equal masses of the electron and the positron in this case. On the other hand, if a body moves with velocity $\mathbf{v}$ relative to the observer, one has $m = m_0/(1 - \mathbf{v}^2/c^2)^{1/2}$ in (2.1). A popular saying is that mass increases with velocity, although Einstein objected to talking about the mass of a moving body (letter dated June 19, 1948 to L. Barnett). Einstein preferred to describe the inertia of rapidly moving bodies by the concepts of energy, momentum and rest mass m_0 [2]. In any case, no rocket can exceed the velocity of light. Just to reach $|\mathbf{v}| = c$ would require an infinite amount of energy. (That is why science fiction on space travel invented "jumps through hyperspace.") Only massless "particles" such as photons propagate at the speed of light.

of our daily lives, for instance, when cosmic radiation interacts with a gene or a transistor and damages it with a probability between zero and one. Thus, quantum mechanics has destroyed the rigid determinism of classical physics. Fortunately, the statistical *averages* of properties and events in the macroworld, computed with quantum-mechanical probabilities, obey the laws of classical physics to an excellent approximation. Thus, our technical devices are safe, as a rule.

One principal finding of classical physics has remained unchanged by quantum mechanics. In fact, it has been confirmed even more deeply[2]:

> Energy, including the energy equivalent of mass, is a conserved quantity. It can be neither created nor destroyed.

This is the first law of thermodynamics.

2.1.3 Energy Quantity and Quality

Since energy is eternal, why do people worry about economic problems because of energy shortages? The answer is: Although the quantity of energy is conserved, the quality of energy is not. Let us look into both.

The *quantity* of energy contained in an energy carrier is measured by the heat given off to the environment in a chemical (or nuclear) reaction that occurs under precisely controlled conditions, and which takes all reaction partners from an initial state before the reaction to a final reference state. The initial state is characterized by the enthalpy H_1, the final state has the enthalpy H_2, and the heat produced is $Q_{12} = H_1 - H_2$ according to (2.42) in Appendix 1 of Chap. 2. Usually, the temperature of the reference state is chosen as $25°C \approx 298\,K$. Often the pressure is that of the natural environment. The reference state of each chemical element is the most stable, naturally occurring compound of this element.

For carbon and hydrogen these compounds are carbon dioxide (CO_2) and gaseous or liquid water (H_2O). One measures the energy quantities contained in coal, oil, gas, and biomass of given mass or volume by the specific heating value in a controlled combustion process. Fuel and combustion air, both at the same initial temperature T_0, are brought into a reaction chamber (calorimeter), and the combustion products must be cooled down to precisely this initial temperature T_0. The heat that leaves the reaction chamber in this process divided by the quantity of fuel is the heating

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[2]For instance, just to preserve the law of energy conservation for the β decay in nuclear reactions, *Wolfgang Pauli* postulated the existence of an uncharged particle with energy, spin 1/2, and vanishingly small mass in 1930. *Enrico Fermi* called it a “neutrino” in 1940. It was found experimentally in 1956.

Table 2.1 Average specific heating values of primary energy carriers; in kilojoules per kilogram (kJ/kg) and kilojoules per cubic meter (kJ/m^3); 1,000 kJ = 0.278 kWh

Oil	41,900 kJ/kg
(Hard) coal	29,300 kJ/kg
Lignite (raw)	8,200 kJ/kg
Wood	14,650 kJ/kg
Peat	12,600 kJ/kg
Oil gas	40,730 kJ/m^3
Natural gas	32,230 kJ/m^3

value of the fuel. There is an upper heating value and a lower heating value. They differ by the heat that has to be supplied by the environment to liquid water to evaporate it. When gaseous water condenses to liquid water, this heat is recovered by the environment as condensation enthalpy. Therefore, one measures the upper heating value of the fuel if the final state of the water in the combustion products is liquid and the lower heating value if the final state is gaseous [5]. In modern heating systems, condensing-value boilers prevent gaseous water from escaping through the chimney. Instead, water is condensed to its fluid state and adds its condensation enthalpy to heating.

Average specific heating values of primary energy carriers are given in Table 2.1. Different fossil fuels contain different concentrations of carbon and hydrogen. Oxidation of carbon according to the molar reaction equation

$$C + O_2 \rightarrow CO_2 + 394\,\text{kJ/mol}$$

yields roughly 80%, 70%, 60%, and 50% of the energy gained by the combustion of lignite, coal, oil, and gas, respectively. Oxidation of hydrogen according to the reaction equation

$$2H_2 + O_2 \rightarrow 2H_2O + 242\,\text{kJ/mol}$$

provides the rest of the heating value of fossil fuels.

The energy content of nuclear fuel is much higher than that of fossil fuels. According to (2.1), the complete conversion of a mass of 1 g into energy yields 25×10^6 kWh. To get the same energy quantity from the combustion of coal, one has to burn about 3,100 metric tons (t) of hard coal, emitting 8,000 t of CO_2 [6]. A 1,300-$\text{MW}_{\text{electric}}$ nuclear power station with a boiling water reactor generates 25×10^6 kWh of electricity (and about two times more heat) in 19 h; during this time it produces about 0.15 t of nuclear waste in the form of burned-out nuclear fuel rods [7]. If one considers the 25×10^6 kWh of enthalpy from coal combustion and (only) the 25×10^6 kWh of electricity from fission as "useful" energy, one may say that the mass ratio of CO_2 to nuclear waste per generated quantity of "useful" energy is more than 50,000. If one compares electricity generation and assumes an efficiency of 40% for the coal power plant, the mass ratio exceeds 100,000.

Energy *quality* came into the focus of energy science when the energy balances of industrial production processes where analyzed quantitatively. This led energy analysts to differentiate between two components of a given energy quantity: a useful one, called *exergy*, which can be converted into any type of physical work

and measures the quality of an energy quantity, and a useless component, called *anergy*.[3] Entropy reduces exergy and enhances anergy, as (2.45) and (2.47) show. Examples for exergy are the energy of solar radiation, the chemical energy stored in coal, oil, and gas, nuclear energy, potential and kinetic energy, and electric energy. Saying "energy" when talking about these energy carriers is the same as saying "exergy." When combustion processes or friction convert exergy into heat, anergy is produced. A quantity Q of heat at temperature T in an environment at temperature $T_0 < T$ contains only the exergy $Q(1 - T_0/T)$. Heat at the temperature of the environment is all anergy.

Exergy drives the machines in mines and on drilling sites, in power stations, factories and office buildings, on rails, roads and farms, in the air, and on the sea. In short, it activates the wealth-creating production processes of industrial economies. Appendix 1 of Chap. 2 presents more physical details on the basic forms of energy and exergy.

In terms of exergy and anergy the first law of thermodynamics says that

$$Energy \equiv exergy + anergy = constant. \tag{2.2}$$

In all energy-conversion processes, which produce entropy, useless anergy increases at the expense of useful exergy. This is meant by "energy consumption."

2.2 Sun and Earth

The Sun maintains life on Earth. It has provided all the energy carriers that are presently used in our economies, except for uranium, and is the source of the principal renewable energies, which will become important in the future. Absorption and re-emission of the energy from the Sun controls our climate, whose stability is part of the general framework that determines further economic evolution. The basic data on the Sun show the might of the gravity-assisted fusion reactor 150 million kilometers away.

2.2.1 Energy Production in the Sun

The Sun shines because hydrogen (H) is being converted into helium (He) in the central core at a rate of 600×10^6 t/s. Fundamental to the solar fusion process is

[3]The concept of "anergy" has been transferred from medicine and psychology. It has not yet been accepted as widely as "exergy," where "availability" was one of the older names of the latter.

the proton–proton reaction, where a proton (p) combines with another proton in its vicinity to form deuterium (^{2}H), a positron (e^+) and a neutrino (ν). (This first step is extremely slow, because it depends on proton tunneling through the Coulomb barrier and on the weak interaction.) The deuterium, which consists of a proton and a neutron, and a proton fuse into helium-3 (^{3}He), where a photon (γ) is emitted. In 85% of the cases two ^{3}He nuclei merge into a ^{4}He nucleus and two protons, and in 15% of the cases a more complicated fusion chain passes through ^{7}Be and ^{7}Li until it terminates in ^{4}He. The proton–proton chain of helium fusion can be summarized by the reaction equation

$$4\mathrm{p} \longrightarrow {}^4\mathrm{He} + 2\mathrm{e}^+ + 2\nu + 2\gamma. \tag{2.3}$$

The kinetic energy released by this reaction is about 26 MeV, where 1 MeV $= 1.6 \times 10^{-13}$ W s. The mass of four protons is bigger by a factor of 1.007 than the mass of a ^{4}He nucleus and the two positron masses. The mass difference between the 600×10^6 t of hydrogen and the fusion product helium is

$$\Delta m = (1 - 1/1.007) \times 600 \times 10^6 \ \mathrm{t} \approx 4.2 \times 10^6 \ \mathrm{t}. \tag{2.4}$$

It is converted into energy E according to $E = \Delta m \times c^2$, Einstein's equation (2.1). Thus, the solar photoluminosity, i.e., the energy emitted per unit time by the Sun in the form of photons, is

$$L \approx 4.2 \times 10^6 \ \mathrm{t/s} \times c^2 = 3.845 \times 10^{26} \ \mathrm{W}. \tag{2.5}$$

(A small part of the power of 4.2×10^6 t/s $\times c^2$, namely, $0.023L$, is carried away by the neutrinos.) In addition to the mass loss of 4.2×10^9 kg/s because of photon and neutrino production and emission, the solar wind blows another 10^9 kg/s away. Thus, during its lifetime (from its birth until now) of about 4.5 billion years (equivalent to 1.4×10^{17} s) the Sun has lost less than 10^{27} kg. This is negligible with respect to its mass of

$$M = 1.99 \times 10^{30} \ \mathrm{kg}. \tag{2.6}$$

The solar fusion process may last for another five billion to ten billion years.

The solar mass occupies the volume of the solar sphere with a radius of

$$R = 6.96 \times 10^5 \ \mathrm{km}, \tag{2.7}$$

and the Sun's mean density is $\rho = 1.41$ g/cm^3. This is 1.41 times the density of water at 4°C. About 92% of the Sun's atoms are hydrogen, nearly 8% are helium, and all other elements make up 0.1% of the total. The mass fraction of hydrogen is 74%, of helium is 24% and of all other elements is 2%. The vast bulk of the Sun is highly ionized, and the free electrons make it an extremely good electric conductor.

Energy production by hydrogen–helium fusion is largely confined to a small volume within 1.4×10^5 km of the Sun's center. There, the temperature exceeds 10^7 K, and pressure is about 10^{10} atm. In the center itself, the temperature is 1.5×10^7 K, and the density of matter is larger than that of water by a factor of 150.

It takes time for the energy to get out of the Sun into space. The main transport process from the center up to about 500,000 km through 98% of the Sun's mass is diffusive radiation. "Radiation is emitted when hot electrons collide with atoms. The radiation travels at the speed of light (300,000 km/s) until absorbed. Although in free space radiation would travel a distance equal to the Sun's radius in little more than 2 s, absorption is so strong inside the Sun" the photon mean free path being typically a fraction of 1 cm, "that it takes 1 million to 2 million years to diffuse out. Thus, the light and warmth we receive were produced near the Sun's center over a million years ago" [8].

Convection, i.e., the transport of heat by the motion of hot gases (or fluids), takes over from about 500,000 km up to the photosphere at the surface of the Sun. There, in electron–hydrogen collisions, negative hydrogen ions are formed. These emit the vast bulk of sunlight and solar radiation. The associated effective solar surface temperature $T_{S,\mathrm{eff}}$ is obtained from the Stefan–Boltzmann law. This law says that the energy flux density Q emitted by a body of temperature T and emissivity ε is

$$Q = \varepsilon\sigma T^4 \tag{2.8}$$

with $\sigma = 5.67032 \times 10^{-8}\ \mathrm{W/m^2K^4}$ being the Stefan–Boltzmann constant. Using the black-body emissivity $\varepsilon = 1$, the luminosity L of (2.5), and the solar radius R of (2.7), one obtains from (2.8)

$$T_{S,\mathrm{eff}} = (L/4\pi R^2\sigma)^{1/4} = 5777\ \mathrm{K}. \tag{2.9}$$

The power L emitted by the Sun spreads into space as a continuous flow of spherical electromagnetic radiation. When this energy flux hits the top of Earth's atmosphere after having travelled across the distance

$$D = 149.6 \times 10^6\ \mathrm{km} \tag{2.10}$$

it has thinned out to

$$S = L/4\pi D^2 = 1{,}367\ \ \mathrm{W/m^2}. \tag{2.11}$$

This irradiance at the mean Sun–Earth distance D is also called the "solar constant." Like the luminosity L, it is the integral over the electromagnetic spectrum. It is the solar quantity primarily accessible to measurement by balloon, rocket, and satellite experiments, and from it the solar luminosity is deduced. All solar models have to give results which are compatible with these basic data.

About 30% of the solar irradiance S, the so-called albedo α, is reflected back into space. Thus, at the top of Earth's atmosphere the power flux

$$S(1-\alpha)/4 = 239\,\mathrm{W/m^2} \tag{2.12}$$

is absorbed. The factor 1/4 is the quotient of the cross-sectional area and the surface area of the Earth. (Here, the Earth is approximated by a sphere of radius R, so the surface area is $A_\mathrm{E} \approx 4\pi R^2$, and the cross section is πR^2.) The product of $A_\mathrm{E} = 510 \times 10^6\,\mathrm{km^2}$ with 239 $\mathrm{W/m^2}$ yields the solar power P_solar absorbed by the Earth as

$$P_\mathrm{solar} = 1.2 \times 10^{17}\,\mathrm{W}. \tag{2.13}$$

This solar power has produced the stock of fossil fuels and grows all biomass on Earth. More about the Sun can be found in [8–12].

Finally, there is the stock of energy that is not a gift of the Sun. In the Sun's atmosphere one observes traces of heavy elements. These elements, quite common to us on Earth, can only be generated in fusion processes at temperatures much higher than those in the core of the Sun. Temperatures above 10^8 and 10^9 K occur in contracting stars which have burned up all their hydrogen and fuse higher elements. Up to iron (^{56}Fe) these fusion processes produce energy. The fusion of elements heavier than iron, however, consumes energy. This energy may have been provided by novae and supernovae. Thus, the Sun, the Earth, and everything on Earth itself have been processed through the inside of at least one star. Especially uranium, the heaviest natural element in the periodic table, is most probably the product of a stellar explosion before the time of our Sun. Its fission into lighter elements with a total mass less than that of the original nucleus liberates some of the energy caught in it during a cataclysmic cosmic event.

2.2.2 *The Natural Greenhouse Effect*

The simplest quantitative description of the natural greenhouse effect considers the Earth in radiative equilibrium with the Sun. In this equilibrium the total solar power that arrives at the top of the atmosphere is

$$P_\mathrm{top} = 1.7 \times 10^{17}\,\mathrm{W}. \tag{2.14}$$

The solar irradiance, i.e., the power flux at the top of Earth's atmosphere, is given by the solar constant S in (2.11). According to (2.12), Earth's biosphere absorbs the power flux $S(1-\alpha)/4 = 239\,\mathrm{W/m^2}$; the spectral range of wavelengths is between 0.2 and 2 μm. This power is radiated back into space in the spectral range of the infrared between about 5 and 30 μm. The required effective temperature T_eff can be calculated from the Stefan–Boltzmann law (2.8). The equation

$$S(1-\alpha)/4 = \sigma T_\mathrm{eff}^4 \tag{2.15}$$

yields

$$T_{\mathrm{eff}} = 255\,\mathrm{K} = -18°\mathrm{C}. \tag{2.16}$$

The solid surface of Earth, however, has an average temperature of 15°C (288 K). At this temperature the Stefan–Boltzmann law yields a radiated power of 390 W/m^2. The difference of 151 W/m^2 between the power emitted by Earth at the bottom and the top of its atmosphere is trapped by the infrared-absorbing trace gases. Trapping so much heat radiation, these gases provide the life-cradling warming blanket around the Earth. They play roughly the same role as the glass roof and glass walls in a greenhouse: Visible sunlight passes through the glass almost unhindered and is absorbed by the plants and soil inside the greenhouse, which are thus warmed up. The heat in the infrared range, radiated by the warmed plants and soil, is absorbed by the surrounding glass, and is then emitted partly to the outside and partly back to the inside. Because of this back-radiation of heat, the temperature inside the greenhouse rises to a level higher than the outside temperature.[4]

The infrared-active gases in the atmosphere, their concentrations in parts per million (ppm), and their contributions to the temperature enhancement above −18°C are as follows: water vapor, H_2O (from 2 ppm to 3×10^4 ppm, 20.6°C), carbon dioxide, CO_2 (preindustrial 280 ppm, 7°C), ozone (near the ground), O_3 (0.03 ppm, 2.4°C), nitrous oxide, N_2O (0.3 ppm, 1.4°C), methane, CH_4 (1.7 ppm, 0.8°C), and others (0.6°C).

Figure 2.1 shows schematically the energy flows associated with the natural greenhouse effect. Here, the incoming solar radiation at the upper limit of the

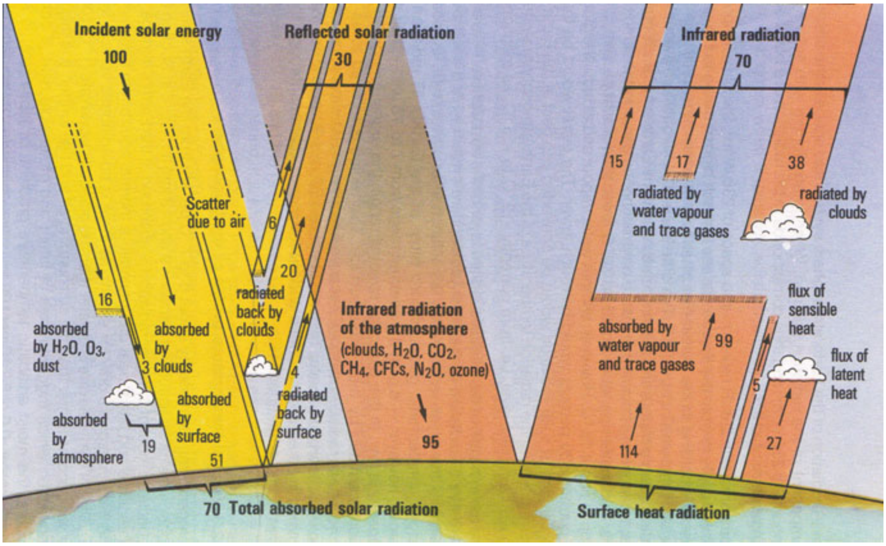


Fig. 2.1 Radiation budget of Earth's surface/atmosphere system [13]

[4]Inhibition of convection by the glass roof also contributes to warming.

atmosphere is given the reference value 100%. Twenty-six percent of it is reflected by the clouds and 4% by the surface – the sum makes up the albedo. The atmosphere swallows 19% (clouds 3%, water vapor, ozone, and dust 16%), and the surface absorbs 51%. Thus, Earth's net absorption of the incoming solar energy is 70%. All this has to be radiated back into space. This occurs partly directly and partly through the buffer of the greenhouse gases in the atmosphere. Let us first see how the surface gets rid of the absorbed 51%. It emits 15% as infrared radiation directly back into space and sends 32% via convection as sensible heat (5%) and latent heat (27%) into the atmosphere. The remaining 4% is the difference between an upward and a downward energy flow in the infrared radiation field caused by the greenhouse effect: The infrared-active trace gases radiate heat down to the surface. The energy of this heat is huge, namely, 95% of the reference value. In infrared-response the surface radiates back 99%. Thus, energy absorption and energy emission are balanced for the surface. The same is true for the atmosphere: 19% absorbed from the incoming solar radiation plus 32% and 4% received from the surface are emitted into space. Adding the 15% of Earth's direct infrared radiation into space yields the 70% absorbed by Earth's surface/atmosphere system as a whole, and the law of energy conservation is satisfied on all levels.

2.2.3 Solar Activity and Climate

The data given for the solar luminosity L and the effective solar surface temperature $T_{S,\text{eff}}$ are valid only as averages over the solar surface and time. A closer look, first done by Johannes Fabricius in 1610 and Galileo Galilei about the same time, reveals dark spots on the Sun, the number of which varies with an 11-year cycle. In these sunspots magnetic flux penetrates the surface of the Sun. This flux blocks the convective energy transport to the surface so that in the sunspots the temperature is only about 4,000 K. Variations in the number of sunspots are the most easily detectable sign of variations in solar activity. The more sunspots, the more active is the Sun. Increasing and decreasing with the number of radiation-blocking sunspots is the number of radiation-enhancing brighter regions, called faculae and plages, where faculae cover an area up to four times that of the associated sunspots and are about 1,000 K hotter than the surrounding photosphere [14]. Thus, all solar emissions exhibit an 11-year periodicity. Correlated with this periodicity is a small but significant modulation of the solar constant S by about 2 W/m^2, S being maximum when the sunspot number is maximum. This 11-year modulation comes from two sources of mutually counteracting effects: enhanced emissions from bright faculae during solar maximum and enhanced blocking by sunspots – obviously the former wins over the latter. In addition to the 11-year sunspot cycle and the associated 22-year magnetic cycle, one has observed long-term secular changes of sunspot cycle amplitude, the so-called Gleissberg cycle. There are also short-duration, sporadic events, such as solar flares, the sun-controlled solar wind shocks, and reversals of the interplanetary magnetic field.

Whether varying solar activity has a perceptible impact on terrestrial climate is a subject of ongoing controversial debate. The "yes" advocates point to empirical findings such as the following ones:

1. Tree rings, which are thicker in wet years and thinner in dry years, show a periodicity of 22 years, the solar magnetic period [8].
2. Carbon-14 is produced by cosmic-ray bombardment of nitrogen. During times of high solar activity these rays are deflected from the Earth by impulsive solar flares, resulting in an anticorrelation of galactic cosmic ray flux with sunspot number. Measurements of the amount of carbon-14 in tree rings has enabled the the number of sunspots to be traced back until AD 1000. This number was nearly zero during the "Little Ice Age" in the second half of the seventeenth century and during the cold period in the fifteenth century (Maunder and Spörer minima) [14].
3. All major midwinter warmings that have been investigated occurred during a special dynamic state of the stratosphere which happened only at times of solar maximum [16].

Arguments of the "no" advocates are as follows:

1. The power involved in solar variability is too small.
2. One cannot think of any mechanism responsible for solar–climate effects.
3. The time intervals for correlation studies are too short, it's all just coincidence.

In response to this it is said that the statistics are becoming better and better, and the energy argument is countered by calling upon the fact that the atmosphere–ocean–biosphere system with its large reservoirs of latent energy is a complex, highly nonlinear system, which can behave chaotically, so very small changes in energy input can trigger large global energy redistributions.

Thus, the sun–climate situation is far from being clear. There are forecasts that solar activity will increase until the year 2030 to the highest level ever recorded, but this is contradicted by expectations of a decrease of solar activity in the next few cycles [8]. The uncertainties encountered here seem to be greater than those associated with the anthropogenic greenhouse effect, to be discussed in Chap. 3. Testimony to that is the following statement: "Should another Maunder minimum begin within the next few decades, (as has been suggested by some authors...) then this would clearly offset future greenhouse gas induced climatic change to some considerable degree. However, the magnitude of Man's impact is such that it would still be the dominant factor in future climatic change" [17].

Furthermore, multiple linear regression analyses show "that within recent decades the solar signal systematically decreased whereas the greenhouse gas signal increased to become a dominant factor of climate variability" [18].

2.2.4 Photosynthesis, Respiration, and Food Production

Photosynthesis provides the chemical energy for life on Earth. Respiration converts this energy into work within living organisms.

Solar photons excite electrons in a special type of molecule (chlorophyll) in the photosynthetic reaction centers of plants and some algae. The excited electrons are passed along a chain of molecules, forming a tiny, solar-driven electric current. This current does two jobs. It breaks up water molecules into hydrogen and oxygen atoms, and it turns molecules of adenosine diphosphate (ADP) into the more energy-rich compound adenosine triphosphate (ATP). In a series of chemical reactions sugar (glucose) and oxygen are formed from hydrogen, carbon dioxide, and ATP. In the net input–output balance of the photosynthetic reaction six molecules of water and six molecules of carbon dioxide plus sunlight result in one molecule of sugar and six molecules of oxygen:

$$\boxed{6H_2O + 6CO_2 + \text{ light } \longrightarrow (HCOH)_6 + 6O_2}$$

The energy of the sunlight is essentially transformed into and stored as the chemical energy of sugar and oxygen.

The process of respiration completes the basic cycle of life. Plants and animals liberate the stored solar energy by the recombination of sugar and oxygen in order to perform work. This work may be mechanical work of muscle contraction, electric work when charges are transported, osmotic work when material is transported across semipermeable barriers, or chemical work when new material is synthesized. At the constant temperature prevailing in most cells, a net output of work can be obtained only when some energy is dissipated. This dissipated energy finally ends up in useless heat at the temperature of the environment.

Thus, respiration converts the exergy stored in sugar into the chemical energy of ATP in a balanced sequence of oxidation–reduction reactions:

$$\boxed{(HCOH)_6 + 6O_2 \longrightarrow 6H_2O + 6CO_2 + \text{“38ATP”}}$$

“38 ATP” stands for the energy of about 2,800 kJ, which is stored in 38 ATP molecules. ATP serves as the universal energy currency in all living systems. When at a given time work has to be performed, ATP is converted into ADP and inorganic phosphate and releases its energy in a hydrolysis reaction under controlled conditions. The chemical end products of respiration are carbon dioxide, emitted back into the air, and water [19].

Agricultural technologies put photosynthesis at the service of humans. Edible plants are grown systematically, and livestock grades up plants that are inedible for humans to tasty meat. The chemical energy stored in food powers the human body.

The quantity and plant composition of crops depend on two properties of the biosphere: (1) weather and climate, which are the short-term fluctuations and the long-term cycles of sunshine and rain; (2) the available land and its content of nitrogen, phosphorus, and other useful trace elements, on the one hand, and the absence of noxious salts and pests, on the other hand. Technical progress in tilling the soil, such as the transition from the wooden pick axe to the animal-drawn iron plow, and crop care, such as manuring and the introduction of rotation of crops, increase the crop yield substantially. Domesticated animals make the energy content of grass available to humans. However, the efficiency of producing animal biomass from plants is only about 20%. Thus, in times of population growth and food scarcity,

changing the dedication of pasture to arable land can enhance the production of food energy fivefold. Estimates for different agricultural technologies [20] arrive at the following annual energetic yields per hectare (10,000 m^2), including fallow:

- Rice with fire clearing (Iban, Borneo): 236 kWh
- Horticulture (Papua, New Guinea): 386 kWh
- Wheat (India): 3,111 kWh
- Corn (Mexico): 8,167 kWh
- Intensive farming (China): 78,056 kWh

Hunters and gatherers only get 0.2–1.7 kWh/(ha year). Thus, on the basis of Chinese intensive farming, 50,000 times more people can live on a given area than under the conditions of hunting and gathering [20].

2.3 Amplifiers of Muscles and Brain

Food powers the human body, whose hands perform work and whose brain processes information. Horses, asses, oxen, and mules also convert fodder into work. Food, fodder, and wood were the main sources of chemical energy for economic activities before the Industrial Revolution. Besides, there are the kinetic energies of wind and water. The use of all these energy forms is quantitatively constrained by the technical potential of harvesting the annual input of solar energy into the biosphere. Qualitatively, their conversion into work by muscles, and machines built mostly from wood, had been constrained by the forces organic structures can take and exert. Heat engines changed this situation drastically. They opened up the huge store of fossil fuels accumulated by the Sun on Earth in more than 200 million years. This had two revolutionary consequences. First, a positive-feedback circle was established in which fossil fuels facilitate the cheap production of metals, from which heat engines are built, which make more natural resources accessible. Second, heat engines convert the chemical energies of coal, oil, and gas into work *outside* the limitations of human and animal bodies. Transistors, powered by electricity, further reduce biological limitations. They assist the human brain in processing and storing huge quantities of information. Heat engines and transistors are amplifiers of human muscle and brain power, and as such they have tremendously enhanced wealth creation by work performance and information processing. Their technical details merit attention in order to understand the physical basis of technological changes in the economy.

2.3.1 Heat Engines

We would still be living in agrarian societies if we had no heat engines. They relieve humans from toil, and provide an ever-expanding realm of energy services. Steam engines were the first heat engines that burned fossil fuels. They triggered

the Industrial Revolution, but they are nearly obsolete now. Modern heat engines are steam turbines, diesel engines, gasoline engines, and gas turbines.

2.3.1.1 Steam Engine and Modern Heat Engines

Steam engines and steam turbines are heat engines with external combustion. Gas turbines, diesel engines, and gasoline engines operate with internal combustion. In external combustion heat flows from a furnace or a reactor into a boiler and generates steam. The energy of the hot steam under high pressure is then converted into mechanical work. In internal combustion engines ignition converts the chemical energy of the fuel into heat, which spreads explosively throughout the gas. Then work is performed at the expense of internal energy.[5]

In the steam engine a piston is pushed back and forth in a cylinder by the steam fed from the boiler into the cylinder by either one or two inlet valves, so the pressure of the expanding steam operates either on one side or on both sides of the piston. After a mass of steam has given off its energy, it is ejected through outlet valves. The motion of the piston can be transmitted by a crank to wheels, e.g., in steam locomotives or old steamships, or to the moving parts of working machines. Control of the engine is facilitated by an indicator, which plots a diagram of the different phases of operation: high-pressure steam injection, expansion, ejection of the relaxed steam, and compression of the residual steam in the cylinder.

The steam turbine is the heat engine with the highest power limit, this limit being set by the corrosion of steel at steam inlet temperatures above 540°C; the outlet temperature is given by that of the environment, or the available cooling water, and is usually not below 30°C. Since the efficiency of heat engines increases with the difference between the inlet and the outlet temperatures according to (2.17), considerable efforts aimed at energy conservation go into materials research. The aim is to find coatings for the surfaces of the turbine blades that will make them less susceptible to corrosion at higher steam temperatures. In contrast to the steam engine, in the steam turbine the pressure of the steam is not used directly for work performance. Rather, it is first transformed into the high velocity of steam molecules, when the steam expands in nozzles, which direct it onto rotor blades. Hitting these blades, the steam molecules give off their kinetic energy to the blades and set the rotor in motion. This motion then drives the propellers of steamships, the pinion gear of machines, and the electricity generators of modern conventional or nuclear power plants. In these plants the steam-generating boiler is heated either by furnaces burning fossil fuels or by heat exchangers through which the coolant of a nuclear reactor runs.

[5]Equations (2.27), (2.28), and (2.38) in Appendix 1 of Chap. 2 indicate how internal energy, i.e., chemical energy, is calculated and measured.

In diesel and gasoline engines the combustion of an air–fuel mixture performs work within a (thermodynamic) cycle consisting of four steps:

1. Air, into which fuel will be injected, or a fuel–air mixture, is sucked into the combustion chamber through the inlet valve; subsequently, it is compressed adiabatically (i.e., without exchange of heat with the environment) by the piston.
2. In gas engines a spark plug ignites the mixture and the gas heats up at constant volume. In diesel engines, after fuel injection and self-ignition, the gas heats up at constant pressure.
3. The hot gas expands adiabatically, driving the piston down, delivering its energy via the piston to the shaft drive.
4. The gas, cooling down at constant volume, is ejected through the outlet valve and the exhaust.

Gasoline engines power cars, aircraft, and outboard motors. Diesel engines drive cars, trucks, locomotives, ships, and electricity generators .

Gas turbines deliver mechanical power either via shaft drives or in the form of jet power, using the kinetic and thermal energy of hot or combustion gases to drive turbine wheels. Normally, one or more compressors compress air and transport it into one or more combustion chambers, where fuel is injected and ignited. The energy-rich gas is carried away into one or more turbines, where it is decompressed so much that the power required by the compressor(s) can be supplied. Then the remaining energy is transformed into mechanical work by another turbine, coupled to a shaft drive; alternatively, in jet engines, the pressure energy accelerates the exhaust gases to velocities between 500 and 800 m/s at takeoff. The thrust-generating gas turbine powers more than 90% of world air transportation capacity. In combination with shaft drives, the gas turbine is used in helicopters, locomotives, ships, pumping stations, gas-turbine power stations, and combined gas-turbine and steam-turbine power stations. Because of its increasing profitability, the gas turbine is often considered as the final stage of the heat engine.

2.3.1.2 Carnot's Ideal Heat Engine

The physical principles of conversion of heat to work were analyzed by the French officer-engineer *N.L.S. Carnot*, who, in 1824, founded thermodynamics with his article entitled "Réflexions sur la puissance motrice de feu et sur les machines propres à développer cette puissance." He investigated the theoretical construction of an ideal heat engine, which now bears his name. This engine consists of a gas in a cylinder, which is closed by a movable piston. It operates between a heat source of absolute temperature T and a heat sink of lower temperature T_0 in four *reversible*, infinitely slow subprocesses $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1$, which represent the Carnot cycle. In process $1 \rightarrow 2$ the gas is compressed adiabatically, i.e., in thermal isolation. Process $2 \rightarrow 3$ is isothermal decompression at constant absolute temperature T. Adiabatic decompression then follows in process $3 \rightarrow 4$.

Isothermal compression at temperature $T_0 < T$ closes the cycle in process $4 \rightarrow 1$. During isothermal expansion(process $2 \rightarrow 3$), the gas absorbs the amount Q of heat from the heat source at temperature T, and during isothermal compression (process $4 \rightarrow 1$), it rejects a smaller amount of heat $Q_{0C} < Q$ to the heat sink, e.g., the environment, at the lower temperature $T_0 < T$. The difference between received heat Q and rejected heat Q_{0C} is the work W_C the Carnot heat engine performs. In general, the energetic efficiency of a heat engine that receives the heat Q and rejects the heat Q_0 is defined as $\eta \equiv W/Q$, with $W = Q - Q_0$. Carnot showed that for the ideal heat engine this efficiency is

$$\eta_C \equiv W_C/Q = (Q - Q_{0C})/Q = 1 - T_0/T. \tag{2.17}$$

The *Carnot efficiency* η_C determines the exergy of heat, which is $\eta_C Q$. Since, in principle, fossil fuels, solar radiation, and nuclear reactions can produce heat sources of absolute temperatures far above those of the environment, i.e.,$T \gg T_0$, so $\eta_C = 1$, their enthalpy is practically all exergy.

No heat engine can have a higher efficiency than the Carnot efficiency η_C. If the heat sink is the natural environment with $T_0 \approx 290\,\text{K}$ and the heat source has a temperature T of, say, 900 K, then η_C is close to 68%. Real heat engines, which complete one cycle not infinitely slowly but within a fraction of a second, dissipate energy by internal friction and turbulences. The pure engine efficiency in motor cars is 20–25% for diesel engines and for gas engines is somewhat lower. Steam turbines have efficiencies up to 40%, whereas the efficiency of gas turbines is higher.

2.3.1.3 Historical Note: Newcomen's and Watt's Steam Engines

Newcomen's engine is shown in Fig. 2.2. It was used industrially for the first time in 1711, when it replaced a team of 500 horses that had powered a wheel to pump out a coal mine. It consisted of a boiler A, where the steam was generated. This was usually a haystack boiler, situated directly below the cylinder. It produced low-pressure steam, all that the current state of boiler technology could cope with. Steam at this pressure would be unable to move a piston of any size. One side of the beam was attached by a chain to the pump at the base of the mine, and the chain at the other side suspended a piston within a cylinder B. The cylinder was open at the top end to the atmosphere above the piston P. The piston had a bevelled edge, around which hemp rope, kept in place by metal weights, acted as a primitive seal. (The rope was kept wet, so that it would expand against the sides.) When the valve V was opened, the steam was admitted into the cylinder. After this valve had been closed, valve V′ was opened to allow cold water from the tank C into the cylinder, thus condensing the steam and reducing the pressure under the piston. The atmospheric pressure above then pushed the piston down in the power stroke. This raised the working parts of the pump, but their weight immediately returned the beam to its original position. Steam was then readmitted, driving the remains of the condensate out through

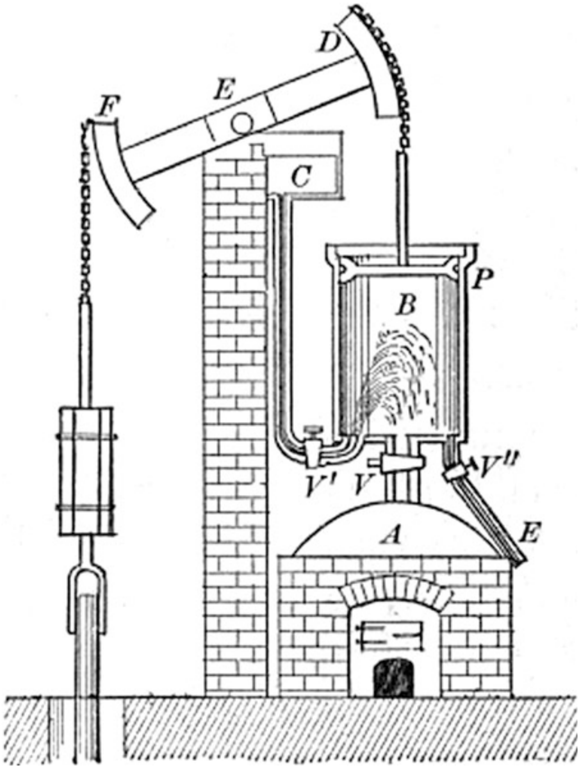


Fig. 2.2 Newcomen's steam pump [21]

a one-way snifter valve V″ as the process started all over again. Unfortunately, the water also cooled the cylinder walls, so when the next charge of steam was introduced, a considerable part was spent simply warming the cylinder back up to boiling temperatures, condensing while this occurred. This reheating of the cylinder consumed much energy. The efficiency of Newcomen's steam engine was 0.5%.

James Watt's first improvement of Newcomen's steam engine was enhancing its energetic efficiency by a separate condensing chamber C; see Fig. 2.3. The cooling water spray was injected into this condensing chamber, attached to the main cylinder B through a valve V′. When the piston P had reached the top of the cylinder, the valve V was closed, so that no more steam from the boiler entered the cylinder B, and valve V′ was opened. External atmospheric pressure then pushed the steam and piston toward the condenser. Thus, the condenser C could be kept cold and under less than atmospheric pressure, whereas the cylinder B, connected to the boiler, remained hot.

Watt further developed his pumping steam engine into what became the multiple-purpose steam engine by substituting low-pressure steam for atmospheric pressure and providing rotary power. A double-acting engine, in which the steam acted alternately on the two sides of the piston, gave a very even movement of the beam. The reciprocating motion of the piston was transformed into rotational power

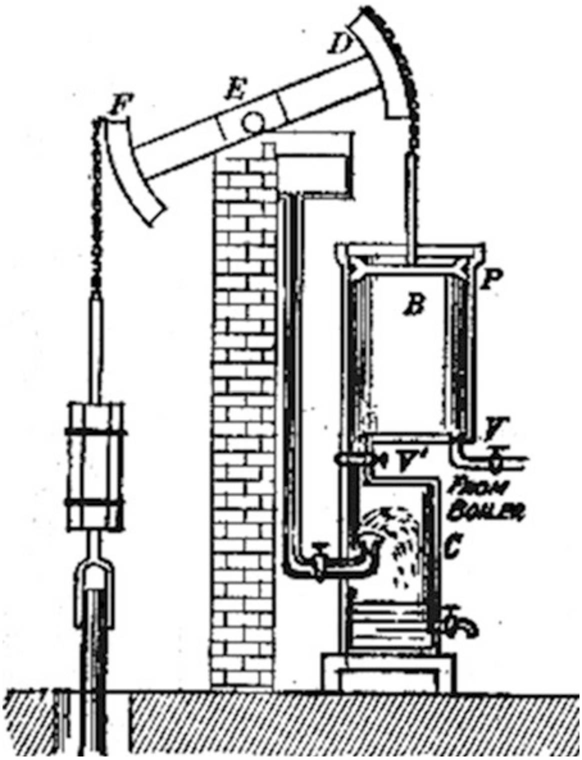
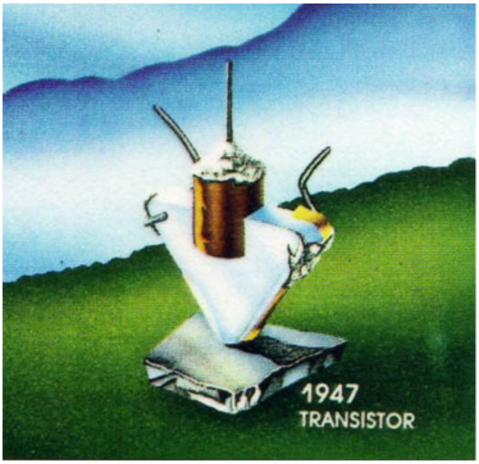


Fig. 2.3 Watt's pumping steam engine [21]

for grinding, weaving, and milling by means of the sun and planet gear system invented by Watt's employee William Murdoch. Later, the more familiar crankshaft was adopted. This allowed the steam engine to be used to replace water wheels, eliminating geographical constraints on the utilization of rotary power.

To improve reliability, Watt introduced further improvements. The operation of the condenser was assisted by an air pump, driven by an eccentric rod attached to the beam. As the pace of the operation of the machine increased, it needed to operate at a constant speed. A centrifugal governor, earlier used in windmills to automatically control the pressure between the millstones, was installed for automatically controlling steam flow to the engine and keeping it at a steady speed. Watt also introduced the manometer to measure steam pressure within the engines. This, when connected to a linkage to the position of the piston and a pencil that recorded both, could record the action of the machine throughout the cycle, producing the indicator diagram. The efficiency of Watt's steam engine was eventually 3%.



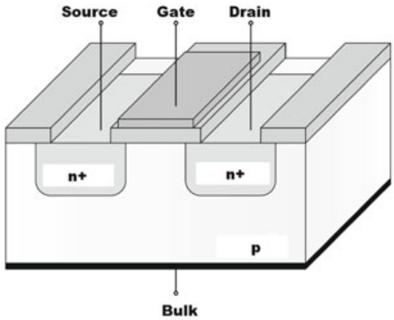


Fig. 2.4 *Left*: Model of the first transistor presented at the celebration of John Bardeen's 80th birthday at the University of Illinois at Champaign-Urbana. *Right*: An n-channel metal–oxide–semiconductor field-effect transistor

2.3.2 *Transistors*

The metal–oxide–semiconductor field-effect transistor (MOSFET) shown in Fig. 2.4 consists of the following elements:

1. The p-type bulk material. This is silicon doped with acceptors. Acceptors are atoms that accept and bind electrons to themselves, leaving positively charged, mobile holes in the valence band of silicon.
2. Two n+-type regions close to the surface of the p-type bulk. The n+-type regions are silicon heavily doped with donators. Donators are atoms that donate negatively charged, mobile electrons to the conduction band of silicon. Two metallic contacts, source and drain, connect the n+-type regions to the rest of the electronic circuit.
3. Three separate stripes of insulating silicon dioxide on top of the p-type and n+-type regions. The center stripe is connected to a metallic contact, the gate.
4. The most important part is the (invisible), 5–10-nm-thick n-type inversion channel between the two n+-type regions. It forms at the surface of the p-type silicon when a positive voltage is applied to the gate, depleting this region of holes. Current is conducted through it only when the positive gate potential is high enough to attract electrons from the source into the channel. When zero or negative voltage is applied between the gate and the source, the channel disappears and no current can flow between the source and the drain. Thus, by varying the gate voltage, one varies the number of electrons in the inversion channel and the conductivity of the device. This way the MOSFET can act as an amplifier of electromagnetic signals in telecommunications or as a valve for

electric currents. Digital information processing is done by blocking or letting pass a current through the inversion channel below the gate: no current flow represents the number 0, current flow represents the number 1.

Since the 1960s the transistor has superseded the vacuum tube in electronics. Substituting the transistor for the bulky, massive, and energy-consuming vacuum tube has saved enormously on materials, energy, and space. For instance, a vacuum-tube computer with the computing power of a 2008 notebook computer would have had a volume of many thousands of cubic meters. According to "Moore's law," transistor density on a microchip has doubled every 18 months during the last four decades. It may continue in that way for a while until the joule heat, produced by the currents circulating in the transistors, can no longer escape sufficiently rapidly to prevent a meltdown of the microchip.

2.4 Energy Services

The wealth of industrial nations has grown so much thanks to energy services from heat engines and transistors[6] that all other countries try to industrialize rapidly, despite the emerging collateral damage pointed out in Chap. 3. Economists interpret the energy services that heat engines and transistors provide under the control of human hands and brains as enhanced labor productivity.

2.4.1 Freedom from Toil

The liberation of humans from hard and dangerous work is arguably the most important energy service provided by machines. Tilling the soil, excavating foundations, lifting weights, drilling holes, breaking and hewing stones, processing metals, and transporting goods and people draw so much on the maximum power of about 100 W an average human can supply that agrarian societies could hardly do without complementing the work of domesticated animals by slavery and socage.

Heat engines provide industrial societies with energy services that are numerically equivalent to that of a mighty workforce of humans. To provide a quantitative idea, let us consider the economy of the Federal Republic of Germany before reunification. In 1990 it consumed 7400 PJ of final energy, approximately 40% of which entered heat engines [22]. This includes electric devices, which may be considered as extensions of the heat engines in power stations. The corresponding power input into heat engines was 8.22×10^{11} kWh/year $= 9.39 \times 10^{7}$ kW. The

[6] Switching devices such as relays and vacuum tubes are now information processors of minor importance.

average human daily work-energy requirement in the form of food for a very heavy workload is 2.9 kWh, corresponding to an average power input of 0.12 kW. Although heat engines are energetically more efficient than humans, let us assume for the sake of simplicity that their output of work per unit of energy input is the same as that of humans. Then the work performed by West German heat engines in 1990 would have been energetically (at least) equivalent to the work performed by $9.39 \times 10^7/0.12 = 780$ million humans laboring 365 days per year.

More specifically, a comparison of forces and powers illustrates the progress introduced in agriculture by farming tractors. Deep plowing requires forces of about 1,500 N. (The tractive power of a horse is about 780 N. On average, humans can pull with a force of about 570 N for short times, and with much less in continuous operation.) For plowing 1 ha of land, and assuming a plow–furrow width of 1 m, one has to apply the force of 1,500 N along a length of 10,000 m. In so doing, one has to perform total work of $1.5{\times}10^7$ J, as one can compute from (2.32) in Appendix 1 of Chap. 2. If four men could work continuously, each at his maximum power of 100 W, they would have performed an amount of work equivalent to that of plowing 1 ha after 10.5 h. Two horses, each working continuously at 700 W, would require 3 h. Diesel engines of farming tractors, running at nominal powers[7] between 20 and 200 kW, would deliver $1.5{\times}10^7$ J within a couple of minutes. (Of course, a tractor needs more time for pulling its plows through a hectare.) On the whole, the agricultural energy services of farming tractors, usually driven by diesel oil and serving a wide variety of purposes, exceed those of men and animals by several orders of magnitude. No wonder that now in industrial countries the percentage of total civilian employment in agriculture is only small, as shown in Table 4.1 in Chap. 4. In Germany it decreased from 25% in 1950 to 2.4% in 2009.

Heaving heavy loads in the construction of buildings and cargos from storage sites to transportation vessels and vice versa has been hard work throughout the ages. In our days it is being done by cranes. Consider a container that has a mass of 10 t. Its center of mass has to be craned against the pull of Earth's gravity from a harbor's loading platform to a containership's cargo area at 10 m above the platform. According to (2.19) and (2.32), the crane must perform work of $9.81{\times}10^5\,\mathrm{J} = 0.27$ kWh. If the crane were powered by electricity, and if its owner had to pay €0.2/kWh – the electricity price for German private households in 2009 – the energy price for heaving the container to the ship would be €0.054. By the same reasoning, one finds that an electricity quantity of 4.8 kWh, costing €0.96, would be required to lift a 100-kg mountaineer in a 100-kg seat from sea level to the top of Mount Everest at 8,848 m.

Excavating building pits and drilling holes in the ground to extract matter from the depths of Earth have also been hard and dangerous work for humans. What if fossil fuels became scarce and could no longer power diggers and drillers? Recently, two economists discussed the decline of nonrenewable energy resources. One expected big problems. The other one was more optimistic and reasoned that there

[7]Mc Cormick D-439: 26 kW, Fendt 824: 177 kW.

are many unemployed people in the world who could provide the physical work required for making renewable energies available, for instance, by drilling 1,800-m-deep holes into the Earth's crust to get geothermal energy. But to provide the required drilling power , one would have to chain huge masses of people to winches. The conventional rig used for drilling a 4,000-m-deep hole in preparation for drilling the world's deepest hole of 9,101 m in the project Kontinentale Tiefbohrung (Windischeschenbach, Germany) required a total power of 2,320 kW.[8] Thus, 23,200 people, permanently supplying 100 W, would have been needed to provide the power for this drilling equipment.

Smelting iron from ore in the fire from wood and charcoal, and hammering it into tools, vessels, and weapons kept many hard-working men busy in olden days. Modern blast furnaces burn fossil fuels, mined and transported by heat engines, and turn out iron in quantities unimaginable to the blacksmiths of the past.

2.4.2 Comfort, Mobility, Information

Steam, gas, water, and wind turbines generate electricity, which lightens homes and powers vacuum cleaners, washing machines, dishwashers, refrigerators, and air conditioners. In kitchen stoves wood and coal have been replaced by (joule heat from) electricity and gas for cooking and baking. Until the middle of the twentieth century, most homes in northern latitudes had just one warm room on cold days; an oven or a tile stove burned dirty coal, which had to be carried upstairs from its bunker in the basement. Nowadays, oil and gas are pumped through pipelines over thousands of kilometers from distant wells to local distribution sites, or immediately into buildings. Their burning in efficient boilers is regulated electronically by thermostats, which keep room temperatures at convenient levels everywhere.

Modern materials allow good thermal insulation of homes and reduce fuel consumption substantially. The temperature of the walls of a room determine the temperature we feel in the radiation field of that room. Since we are only comfortable within a narrow temperature range around 20°C $\approx$ 293 K, we program thermostats to correct for small temperature changes ΔT that fall out of this range. If heat losses through walls and windows have lowered the temperature from T to $T - \Delta T$, raising the temperature back to T requires an energy quantity that increases with the third power of T according to (2.25) and (2.26) in Appendix 1 of Chap. 2.[9]

[8] Lifting equipment 1,240 kW, scavenging pumps 720 kW, rotary table 360 kW (F. Holzförster, private communication). The power of drilling equipment units offered by Drill-Quest Engineering in Hünenberg, Switzerland, is 82.9 kW (112 hp) for a stationary diesel power unit and 555 kW (750 hp) for a mobile drilling rig.

[9] The difference between the radiation energy in a room with wall temperature T and the same room with wall temperature $T - \Delta T$ is proportional to $T^4 - (T - \Delta T)^4 \approx 4T^3 \Delta T$.

But few people bother about good thermal insulation of homes as long as they have to invest more in insulation than they can save in fuel costs in, say, 20 years.

A huge gain in traveling comfort and mobility has been obtained since heat engines entered the field of transportation. Until the beginning of the nineteenth century, common people such as journeymen traveled on foot. A daily walking distance was usually not much more than 30 km. Wealthier people, who could afford a carriage drawn by horses, traveled at speeds of about 15 km/h and suffered from poor suspension on bad roads. In our times, we enjoy comfortable seats in well-cushioned cars, buses, and trains going at 80–300 km/h.

Energy balances for a compact passenger car with a total mass of 1,500 kg are as follows. If the car moves at 120 km/h, its kinetic energy is $8.34 \times 10^5\,\mathrm{J} = 0.23\,\mathrm{kWh}$, according to (2.18). The velocity is achieved, and maintained against friction, by a 75-kW gas engine with a gas consumption of, say, 7 L per 100 km when driving at 120 km/h on a flat road during a calm day. (About 100 horses could also supply 75 kW and would need $10^6\,\mathrm{m}^2$ of pasture.) If one could travel at a constant 120 km/h for 5 h, covering 600 km, one would have used 42 L of gasoline, less than a tankful, which cost €59 at a price of €1.40/L. Assuming an energy content of $8.8\,\mathrm{kWh} = 31{,}700\,\mathrm{kJ/L}$ of gasoline, one would have used 370 kWh on the trip, essentially by producing heat via the friction from air and wheels. Braking the car from 120 to 0 km/h dissipates the kinetic energy of 0.23 kWh as heat in the car's brakes. Braking by converting the kinetic energy of forward motion into the kinetic energy of a rotating flywheel within the car could conserve most of the exergy. It could be reused for subsequent acceleration. Since kinetic energy increases with the square of velocity, a car that hits a wall at 50 km/h releases four times more destructive, and often deadly, kinetic energy than the same car hitting the wall at 25 km/h.

Trucks, ships, and airplanes, burning diesel oil and kerosene, move people and freight rapidly over distances that span continents and the globe. Rockets, powered by solid boosters and engines that burn liquid fuels such as hydrogen, transport telecommunication and Earth-observation satellites to low and high Earth orbits.

Telecommunication via telegraphs, phones, radio, TV, and the Internet makes more information available to the modern individual than his or her brain could ever process and store. This is quite different from the times when letters and books where the only carriers and stores of information outside the human body. Information in telecommunication is imprinted upon electromagnetic waves that propagate through metallic wires, the air, and a vacuum. Their energy density (in a vacuum) is given by (2.22) in Appendix 1 of Chap. 2. One source[10] estimates that "power consumption of telecommunications and data networks ... (is) as much as 3% of European electricity".

Electric energy also serves information processing. Electric waves carry information to a computer's processor, which consists of transistors. Either a 1 (electric

[10]http://www.optoiq.com/index/photonics-technologies-applications/lfw-display/lfw-article-display/articles/optoiq2/photonics-technologies/news/applications-_markets/communications-_it/2010/8/BIANCHO-project.html.

current) or a 0 (no current) is received per cycle. The rate at which the wave pulses enter the processor is measured in cycles per second, i.e., hertz (Hz). This determines the speed of information processing. Modern computers are so fast that this rate is measured in billions of cycles per second, i.e., gigahertz (GHz). The battery of a 2.4-GHz laptop, which stores about 0.06 kWh when new, is emptied within 1–2 h of operation. Quite a bit of this energy is consumed for ventilating the joule heat developed by the currents in the processor. The higher the pulse frequency, the more joule heat is produced. The fact that haste makes waste will be discussed further in Chap. 3 on entropy production.

2.4.3 Political Power

A nontechnical energy service flows from the ownership of energy sources. This was seen impressively after World War II, when abundant cheap oil powered rapid economic growth in North America and Europe. The party ended abruptly when the Arab members of the Organization of Petroleum Exporting Countries (OPEC)[11] implemented an oil embargo against the West in retaliation for US support of Israel during the Yom Kippur War from October 6 to October 26, 1973. Although the embargo was lifted in March 1974, the OPEC members decided to raise their real incomes from oil exports by raising world oil prices. As a consequence, the inflation-corrected price of a barrel of crude oil in 2009 US dollar prices jumped from about $\$_{2009}15$ in 1973 to $\$_{2009}50$ in 1975. This first "energy crisis" caused the first postwar economic recession. The second energy crisis hit when the price of the barrel climbed to more than $\$_{2009}90$ in 1981, after the Iranian revolution and the Iraq/Iran war had reduced oil supply. Figure 2.5 shows how the price of a barrel of crude oil in constant and nominal US dollars developed between 1861 and 2009. OPEC became a major economic and political player in the world.

The Soviet Union was not an OPEC member but, being a major oil exporter, profitted greatly from the oil price explosions. When the economies of the West suffered from the high oil prices on international markets, the Soviet Union and its allies enjoyed the "socialist" block's low oil prices set by the Soviet planners. Thus, East Germany remained practically unaffected by the two oil price shocks, whereas West Germany went into recession. This caused an East German leader to boast that the superiority of socialism had finally been proven. In 1979 the Soviet president, Leonid Brezhnev, and the politburo of the communist party felt the Soviet Union was strong enough to invade Afghanistan and start an arms race. The navy was reinforced to catch up with US sea power and SS-20 rockets were deployed against western Europe. Then came the third, negative oil price shock, that is, the

[11] OPEC is a cartel of 12 countries made up of Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela. OPEC has maintained its headquarters in Vienna since 1965.

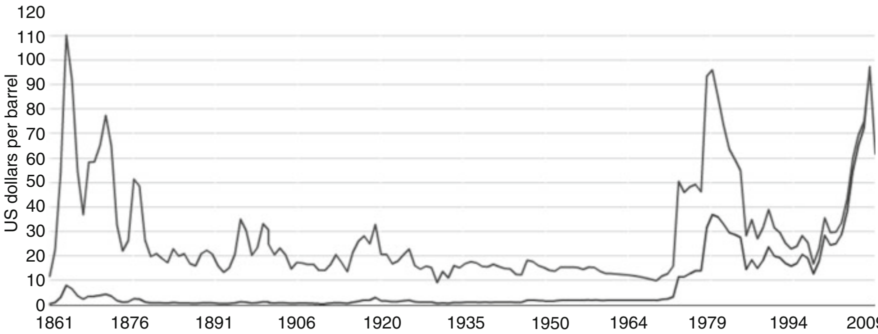


Fig. 2.5 Development of the price of one barrel of crude oil since 1861 in 2009 US dollar prices (*upper curve*) and in dollar prices of the day (*lower curve*); see also Fig. 4.7. (Source: http://www.pdviz.com/historical-crude-oil-prices-1861-to-2009)

fall of the oil price from over $\$_{2009}90$ per barrel in 1981 to just $\$_{2009}30$ per barrel in 1986. The flow of petrodollars into the Soviet Union subsided and could no longer finance the import of urgently needed consumer goods. The nation's resources had mainly gone into heavy industry, whereas the consumer industry remained weak and inefficient under the control of the planning bureaucracy. Realizing the need for change, Mikhail Gorbachev introduced the reforms of perestroika and glasnost, but it was too late. After the collapse of the Soviet Union in 1991, Russia and the other successor states introduced market economics, however without the appropriate legal framework and the institutions to enforce it. This was one cause for the economic and political decline of the former superpower during the decade from 1990 to 2000. The other cause was the low oil price in the 1990s. When the oil price started to rise again at the turn of the century, and its annual average climbed to nearly $\$_{2009}100$ per barrel in 2008, Vladimir Putin rose to power in Russia. He became acting president of the Russian Federation on December 31, 1999, won the presidential elections in 2000 and 2004, and would have been reelected in 2008 had the constitution not forbidden a third term in office. Instead he was nominated to be Russia's prime minister by his successor Dmitry Medvedev. Analysts attribute a good part of Putin's popularity with the Russian electorate to the increase in the standard of living during his reign, thanks to Russia's large revenues from the exportation of oil and gas.

Industrialization of populous emerging economies such as those of China, India, and Brazil, and the resulting growing demand for energy, has driven up the oil price since 1999. Its fall by one third because of the global recession that was triggered by the collapse of the US housing market and the ensuing bank crashes in 2007–2008 is most likely to be temporary. If the global economy recovers despite the huge debts accumulated by governments in their fight to avoid recession, energy prices will rise again. By how much they will rise will depend on the reserves and resources of the traditional fuels, the potential for energy conservation, and the technological

options for exploiting all energy sources that are fed by the natural or technological conversion of mass into energy.[12] Economic and political power will be with those societies that meet best the challenges arising from the energy problem.

2.5 Consumption, And What Is Left

Energy services dissipate the valuable exergy of energy carriers by producing entropy. Equations (2.28) and (2.45–2.47) in Appendix 1 of Chap. 2 indicate how entropy reduces exergy. In this sense, economic activities lead to "energy consumption."

2.5.1 Consumption of Energy Carriers

Average energy consumption per person per day is a rough indicator of material well-being in an economy. However, when comparing it during different times and for different economic systems, one has to take into account differences in energy-conversion efficiencies. In general, a system with higher efficiencies of its energy-converting devices provides more material well-being than a system with lower efficiencies and the same per capita energy consumption. Despite this qualification, the evolution of per capita energy consumption during human history can still be seen as running parallel to the evolution of civilization. Material well-being in this sense can be also illustrated by the average number of energy slaves serving every person in an economy.

> The number of energy slaves in an economy is given by the average amount of energy fed per day into the energy-conversion devices of the economy, divided by the human daily work-calorie requirement of 2,500 kcal (2.9 kWh) for a very heavy work load. Dividing this by the number of people in the economy yields the number of energy slaves per capita.

The following scheme shows the evolution of average energy consumption per person and day and the resulting *per capita* energy slaves from one million years before the present (BP) until our time:

One million years BP: 2 kWh (gatherer without fire).
100,000 years BP: 6 kWh (hunter and gatherer with fire), approximately one energy slave
7,000 years BP: 14 kWh (simple peasant society), approximately four energy slaves

[12]Fusion in the Sun provides all renewable energies, except tidal power and those geothermal energies that result from the radioactive decay of minerals and volcanic activity.

AD 1400: 30 kWh (western Europe), approximately nine energy slaves
AD 1900: Germany 89 kWh, approximately 30 energy slaves
AD 1960: West Germany 61 kWh, approximately 21 energy slaves; USA 165 kWh, approximately 59 energy slaves
AD 1990: West Germany 117 kWh, approximately 40 energy slaves; USA 228 kWh, approximately 79 energy slaves
AD 1995: Germany 133 kWh, approximately 45 energy slaves; USA 270 kWh, approximately 92 energy slaves
World average 46 kWh, approximately 15 energy slaves; developing countries 20 kWh, approximately six energy slaves

Of course, the 21 energy slaves per West German in 1960 worked much more efficiently, i.e., provided more energy services, than the 30 energy slaves per German in 1900, thanks to technical improvements in the energy-conversion devices. Furthermore, the 40 energy slaves per capita in West Germany in 1990 include those that provide process heat and room heating, and which add to the heat-engine energy slaves – roughly 13 per person in 62 million people – calculated in Sect. 2.3.1.

The provision of energy slaves by a production system determines the number of people who can live on a given land area. Hunters and gatherers with fire, who command one energy slave per person, have an average per capita energy consumption of 6 kWh/day, or 2,190 kWh/year. Harvesting plant and animal biomass, they can get between 0.2 and 1.7 kWh/ha/year, as we saw in Sect. 2.2.4. Thus, each member of a hunter-and-gatherer society needs at least 13 km^2 to satisfy his energy needs. Germany's land area of 351,000 km^2 could therefore accommodate at most about 27,000 hunters and gatherers. In 2010, 82 million people were living in industrialized Germany.

Figure 2.6 illustrates how world energy demand grew between 1970 and 2004, and which energy sources satisfied it.

In 2004 global primary energy consumption was 427 exajoules (EJ) $= 427\times10^{18}$ J (approximately 10.198×10^9 t of oil equivalents, approximately 14.571×10^9 t of coal equivalents, approximately 117.483×10^{12} kWh). Oil provided 157 EJ, gas 101 EJ, coal 116 EJ, nuclear power 26 EJ, and other sources 27 EJ (see Fig. 2.6). In 1992 global primary energy consumption was 344.8 EJ, and in 1970 it was 209 EJ. Oil has the biggest share (approximately 40%) of global primary energy consumption, followed by coal and gas.

Primary energy consumption by G7 countries has been more than 40% of global consumption. Table 2.2 gives the shares of the different energy sources in satisfying the demand of these industrial nations. The USA is the biggest energy and oil consumer. Its per capita energy consumption is only slightly smaller than that of Canada, as shown in Table 2.3.

The European G7 countries and Japan are much more densely populated and have much smaller daily per capita energy consumption than Canada and the USA. Furthermore, private households and vehicles use energy more sparingly in Europe and Japan than in North America. Comparison of the data in Table 2.3 with the 1995

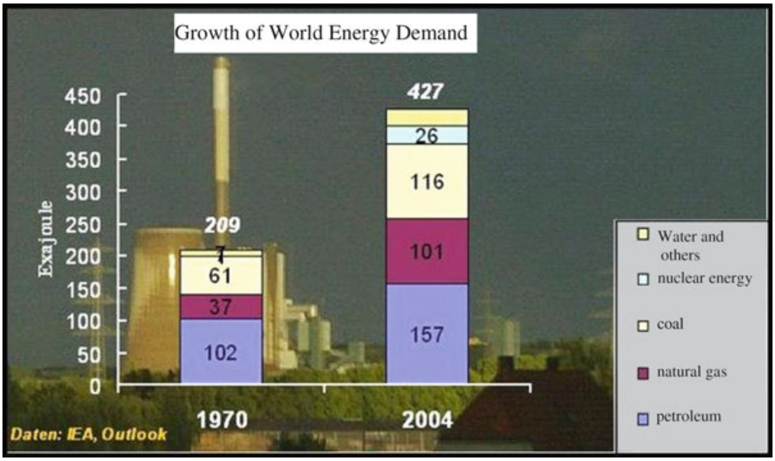


Fig. 2.6 Global energy demand in 1970 and 2004. From *top* to *bottom*: Water and others, nuclear energy, coal, natural gas, mineral oil. 1 EJ = 10^{18} W s; 427 EJ = 10.2×10^9 t of oil equivalents (Source: www.weltderphysik.de)

Table 2.2 Primary energy consumption (million tons of oil equivalents) in the G7 countries Canada, France, Germany, Italy, Japan, the UK, and the USA in the years 1995 and 2003 [23]. (*Others* includes water, geothermal, and solar power, combustion of biomass and garbage, export balances of electricity and heat)

	Coal		Oil		Gas		Nuclear		Others		Total (rounded)	
G7 countries	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003
Canada	25.4	30.0	78.2	91.7	67.1	79.2	25.6	19.5	36.2	40.2	232	261
France	16.1	14.4	86.6	91.0	29.6	39.4	98.3	115.0	10.9	11.6	241	271
Germany	91.0	85.1	135.7	126.5	66.4	79.2	39.9	43.0	5.9	13.3	339	347
Italy	12.3	14.9	94.5	87.4	44.6	63.3			10.1	15.4	162	181
Japan	82.6	107.7	269.6	257.0	52.0	71.0	75.9	62.6	17.0	18.9	497	517
UK	48.6	38.2	84.6	81.4	65.1	85.9	23.2	23.1	3.0	3.3	225	232
USA	475.3	531.2	804.4	921.4	508.7	519.2	186.0	205.3	114.0	103.7	2089	2281
Sum	751.3	831.5	1553.6	1656.4	833.5	937.2	449.5	468.5	197.1	206.4	3785	4090

data in the energy slave listing shows that daily per capita energy consumption in the USA decreased from 270 kWh in 1995 to 246 kWh in 2005. The US population increased from 257.6 million in 1993 to 295.7 million in 2005.

The lifestyle of industrialized countries such as the G7 counties is associated with average energy quantities required for products and activities that are indicated in Table 2.4.

A broader view of energy and oil consumption per person is presented in Fig. 2.7.

Table 2.3 Population of G7 countries in 2005 [24], (approximated) daily per capita primary energy consumption, and the corresponding per capita power consumption

G7 countries	Population (millions)	Primary energy consumption per person per day (kWh)	Power consumption per person (kW)
Canada	32.8	253	10.5
France	60.6	143	6.0
Germany	82.4	134	5.6
Italy	58.1	99	4.1
Japan	127.0	130	5.4
UK	60.4	122	5.1
USA	295.7	246	10.3

Table 2.4 Average energy requirement per product or activity [25]

Good/activity	Energy requirement (kWh)
1 kg bread	10
1 kg book	50
1 kg motor car	200
1 kg laptop	1,000
1 warm shower	5
1 h cell phone conversation	2
1 h watching TV	3
1 university classroom hour per student	20
1 h car driving	200

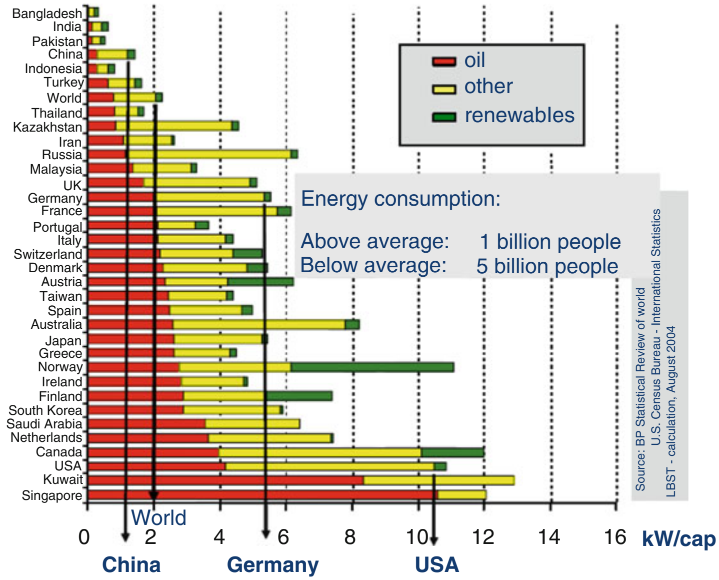


Fig. 2.7 Energy and oil consumption per person (kW/capita) in different countries [26]

Table 2.5 Global and regional reserves of coal (hard coal and lignite), mineral oil, and natural gas in 2005, and their depletion times (*DT*) in years at 2005 exploitation rates [27]. *MtCE* 10^6 t of coal equivalents (equivalent to 29.3 PJ), *MtOE* 10^6 t of oil equivalents (equivalent to 41.9 PJ; 1 t of oil equivalents is equivalent to 7.3 barrels of oil equivalents), *EJ* exajoules; 10^9 m^3 natural gas is equivalent to 32.23 PJ. North America includes Canada, the USA, and Mexico; Europe is without the Commonwealth of Independent States (*CIS*; the former USSR)

	Coal		DT	Oil		DT	Gas		DT
Region	MtCE	EJ	(years)	MtOE	EJ	(years)	10^9 m^3	EJ	(years)
World	656,200	19,227	161	161,600	6,771	41	179,059	5,771	63
Middle East				100,427	4,208	83	72,652	2,342	>200
Africa	47,600	1,395	232	15090	633	32	14,082	454	86
North America	210,400	6,165	213	6,840	286	11	7,737	249	10
South America	15,000	440	246	14,209	595	41	7,174	231	53
Asia/Oceania	170,200	4987	86	6,412	287	17	14,425	465	45
Australia	73,300	2148	256						
CIS	114,500	3,355	369	15,975	669	28	57,123	1,841	70
Europe	25,200	738	99	2,648	111	10	5,866	189	18

2.5.2 Reserves and Resources of Fossil and Nuclear Fuels

Industrial democracies and some oil exporters have enjoyed a boost in the standard of living since the end of World War II. But how long will the party last? The answer depends on the evolution of the reserves and resources of primary energy.

Reserves are the occurrences of energy carriers that have been identified and measured and that are known to be technically and economically recoverable. Resources are all occurrences of energy carriers with less certain geological assurance and/or doubtful economic feasibility [29].

There is a static and a dynamic way of estimating the time after which the finiteness of reserves will become a problem.

The static method considers the reserves of a given year and divides them by the exploitation rates of that year. This gives the depletion times, after which the reserves will be totally gone, if the exploitation rate stays the same until the end. Table 2.5 presents the very unevenly distributed reserves of coal, oil, and gas, and the static depletion times. According to the latter, the global reserves of coal, oil, and gas would be exhausted in about 160, 40, and 60 years, respectively. The estimated global *resources*, which may be exploited – with advanced technologies – at higher cost than reserves are 4.1689×10^{12} t of coal equivalents, 82.056×10^9 t of oil equivalents, and 206.770×10^{12} m^3 gas. Thus, at the exploitation rate of 2005, the resources of *coal* would last for nearly *1,000* years.

The global reserves and resources of the nuclear fuel uranium are given in Table 2.6. The heating value of 1 t of uranium is between 0.4 and 0.7 petajoules (PJ), depending on the reactor type and the fuel cycle; here, we use 0.5 PJ (0.5×10^{-3} EJ). The reserves of natural uranium can be mined at cost up to US $40/kg. The resources of natural uranium can be mined at cost between US $40/kg and US $80/kg; 88% of them are in ten countries. Canada, Australia, Niger, and Russia are presently

Table 2.6 Global reserves, resources, and speculative resources of natural uranium, in million tons (Mt) [28] and exajoules (EJ), in 2005

Reserves		Resources		Speculative resources	
1.95 Mt	975 EJ	5.32 Mt	2,660 EJ	7.54 Mt	3,770 EJ

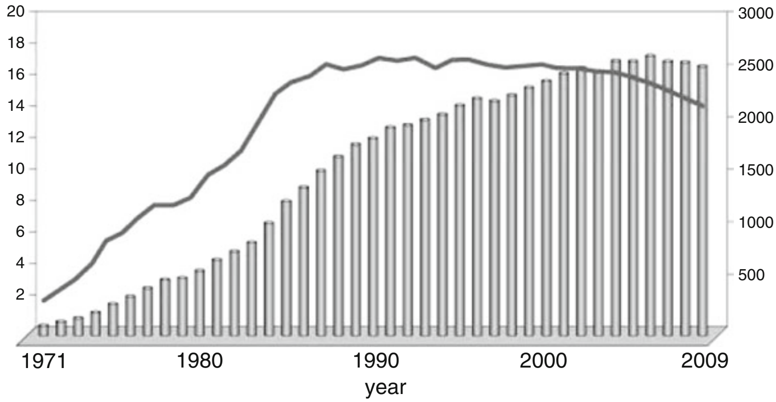


Fig. 2.8 Global nuclear electricity production (TWh/year) (*right ordinate*, *bars*) and percentage of total electricity production (*left ordinate*, *line*) from 1971 to 2009. (Source: World Nuclear Association)

the main suppliers of uranium. The speculative resources include uranium in stocks and especially in old nuclear weapons inventories; the latter contain more fissile uranium-235 (U^{235}) than natural uranium. The concentration of U^{235} in natural uranium is only 0.7%. Global annual uranium consumption was 65,000 t in 2007. About only half of that was mined. The rest was obtained from stocks and the conversion of nuclear warheads to reactor fuel rods.

The potential of thorium as a nuclear fuel is discussed in Sect. 2.6.

According to the World Nuclear Association, the share of nuclear power was 15% of global electricity generation in 2007, when the installed generating capacity of the 439 nuclear reactors was 371.7 $GW_{electric}$.[13] A decade before it was 17%. The growth of nuclear generating capacity and of the number of nuclear reactors between 1971 and 2009 is shown in Fig. 2.8.

The dynamic method of estimating the time after which the finiteness of Earth's energy reserves will cause trouble takes into account that industrial growth is coupled to the growth of energy consumption. An exception to this observation is periods during which energy conservation measures improve the overall energetic efficiency of economies. This happened especially after the first and the second oil price shocks of 1973–1975 and 1979–1981. But there are thermodynamic limits to energy conservation [30]. Once they are reached, increasing exploitation of energy reserves and resources is inevitable if industrial production grows. Given this

[13] http://www.world-nuclear.org/info/reactors.html.

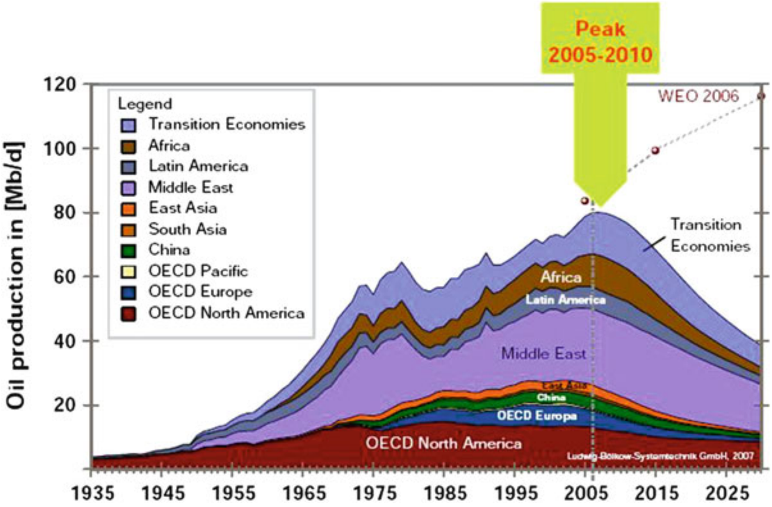


Fig. 2.9 Regional and global oil production in the past and as predicted by the "Peak Oil" theory and the World Energy Outlook 2006 [26]

situation, the Texan oil geologist Marion King Hubbert introduced the concept of "Peak Oil" in 1956 [32]. Since the late 1990s this concept has gained more and more attention. This means that oil production, as a function of time, will increase and then decline inevitably in the form of a roughly bell shaped curve. The maximum of oil production is "Peak Oil". In his book *The Last Oil Shock* David Strahan [33] tells the exciting story of how Hubbert predicted that the USA would reach Peak Oil around 1970, that experience proved him right, and how individuals and institutions with special interests in the oil business tried to suppress his method and findings. By now Hubbert's method is widely used by researchers and is also applied to energy sources other than oil. Figure 2.9 shows global and regional peak-oil scenarios and Fig. 2.10 plots the growth and decline of global fossil fuel and uranium reserves. These scenarios are based on a number of economic and geological assumptions that reflect past experiences. They are not predictions. If they worked as self-destroying prophecies, their authors would be more than happy. Chance is also that the great economic crisis, triggered by the burst of the American mortgage bubble in 2007, will shift the peaks from the near into a more distant future.

2.5.3 Renewable Energies

Biomass, water power, wind power, solar heat, and solar electricity are renewable sources of energy. They originate from solar radiation. Geothermal energy is usually counted as renewable energy too. It originates from radioactive decay of uranium and thorium in the interior of Earth.

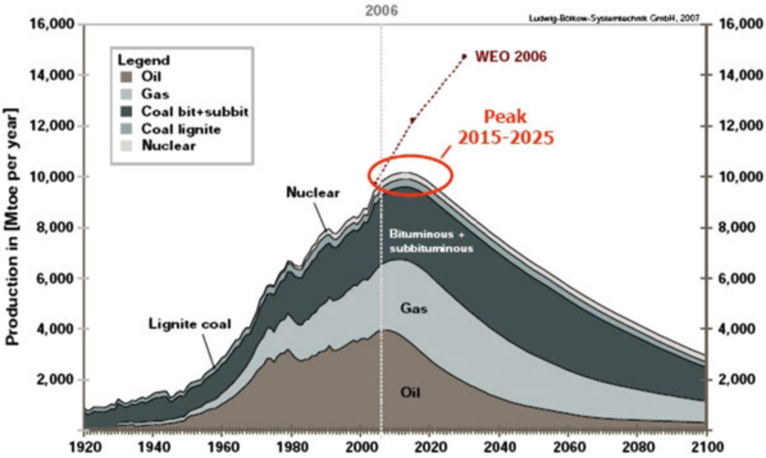


Fig. 2.10 Production of conventional energy carriers in the past and scenarios for the future [26]. *Mtoe* million tons of oil equivalents

With few exceptions, heat and electricity from renewables have been more expensive than heat and electricity from fossil fuels. But when investment costs for exploiting renewables will no longer exceed those for providing and burning fossil fuels, market penetration of renewables will rapidly increase beyond the scope reached so far.

By definition, economic potentials of renewables can be exploited with available technology at costs that are comparable to those of exploiting conventional energy sources. Technical potentials of renewables can be exploited with known technologies that have to be developed further for grand-scale operation. Thus, the economic and technical potentials of renewables correspond (more or less) to the reserves and resources of fossil fuels. The potentials of renewable energy sources are subject to environmental constraints, although probably to a lesser extent than the reserves and resources of fossil fuels.

Renewables generated by solar radiation have the greatest technical and economic potential. This is because of the sheer size of the solar input. Earth absorbs 1.2×10^{17} W of solar radiation power. This is 239 W/m^2 according to (2.12). The solar power influx exceeded global energy consumption of 427 EJ in 2004 by a factor of roughly 10,000, because 427×10^{18}W s/year = 1.35×10^{13} W. Thus, the fusion reactor the Sun is a huge resource that supplies energy free to Earth. It will last for several billion years. However, sunlight reaches the surface of Earth intermittently. One has the problem of storing its energy. Furthermore, one needs large areas. For instance, more than 3×10^6 m^2 is needed just to collect 800 MW of solar radiation. This area increases with the inverse of the efficiency of converting solar radiation into the required final energy, be it heat or electricity. At a first glance, this compares quite unfavorably with the roughly 600 m^2 occupied by a typical 800-MW steam turbine of a fossil-fuel-burning electric power plant. But the area required for

Table 2.7 Solar power farms for a hydrogen economy serving a world population of ten billion people. For two scenarios, the following are shown: the power provided per person, the photovoltaic collector area required, and the amount of steel required for scaffolding, reinforcement, etc. at 10 kg/m^2 [34]

Power per person (kW)	Collector area required (km^2)	Amount of steel required (Mt)
10	4×10^6	40,000
4	1.6×10^6	16,000

providing the fuel and for evaporating the waste heat may exceed the steam-turbine area by several orders of magnitude.[14] Thus, both the abundance of an energy source and the scarcity of areas required by the technology for its supply and utilization are crucial. Area scarcity differs with the type of energy source, geography, and climate.

2.5.3.1 A Global Scenario

An illustrative example of what might be possible under very favorable conditions is an estimate of the areas and materials required for satisfying future global energy demand by solar power. In this example, population growth on Earth is assumed to level-off at ten billion people. All energy demand is satisfied by photovoltaic sun farms in the subtropical desert belt of Earth. They convert sunlight to electricity. The electricity is used to produce hydrogen by electrolysis, thus storing solar energy in an energy carrier that, with some caution, can be handled and used like oil. The example was published in 1975 by Paul Erbrich [34] in an evaluation of the second report of the Club of Rome. Two scenarios were considered. The first one corresponds to a US-like per capita energy consumption of 10 kW. The second scenario considers a per capita consumption of 4 kW, the French consumption rate in the 1970s. The estimate is shown in Table 2.7.

It is still appropriate for giving an idea of the orders of magnitude involved in satisfying future energy demand by solar power. The basic assumptions are as follows: solar radiation density in the subtropical desert belt is 250 W/m^2; the efficiency of photovoltaic conversion of solar radiation to electricity is approximately 20%; the efficiency of electrolytic production of hydrogen is approximately 50%; the efficiency of conversion of hydrogen to energy services (including transportation) is approximately 80%. The total system efficiency is (optimistically) about 10%.

[14] A comparison of geothermal power plants with others by the US Department of Energy estimated the total area per megawatt of a coal-fired power plant to exceed 70,000 m^2 (probably assuming strip mining of coal); http://www1.eere.energy.gov/geothermal/geopower_landuse.html.

For other total system efficiencies one has to scale the numbers in the second and third columns of Table 2.7 correspondingly. Areas for comparison are those of the Sahara (9×10^6 km^2), Saudi Arabia (2×10^6 km^2), and Spain (0.5×10^6 km^2).

The International Iron and Steel Institute announced that world crude steel output reached 1.2395×10^9 t in 2006. This is less than one tenth of the steel demand of the 4 kW/capita scenario. Maybe one can replace steel by concrete. Cost estimates for this scenario were between US \$20 trillion and US \$50 trillion in 1975. Technological progress in the production of photovoltaic cells would decrease that cost, perhaps by an order of magnitude or more. At the 2004 conference on renewable energies in Bonn, the president of the International Solar Energy Society, Yogi Goswani, reported that in 1974 a solar cell cost US \$30/W, whereas by 2004 the cost had dropped to US \$3/W. In 2007 the firm First Solar announced a cost of US \$1.12/W.

Annual photovoltaic electricity production would be 87.6×10^{12} kWh in the sun farm scenario of 4 kW/capita energy services from hydrogen. This would be more than five times the global electricity consumption in 2006, which was 16.379×10^{12} kWh. The globally installed generating capacity grew from 2,900 gigawatts (GW) in 1995 to 4,012 GW in 2006 [35].

2.5.3.2 Individual Potentials

Biomass, the product of photosynthesis, has the longest tradition as a renewable energy source. Its extracorporal energetic use dates back to the taming of fire some 400,000 years ago. Dry biomass with a carbon content of about 50% has a heating value of 17.6 MJ/kg. Annually, on the global average, 12 t of dry biomass is produced per hectare of green land area. Thus, annually the continents of Earth produce 120×10^9 t of dry biomass with a burning value of 2,000 EJ [36]. This is nearly five times the 427 EJ consumed globally in 2004. However, only 80 EJ of that may be combusted as biofuels, because the major part of biomass is needed as food and nonenergetic raw materials [36].

Wood, grain, oil seeds, oil palms, cane, other annual and biannual plants, and organic wastes, e.g., straw and manure, are biofuels. However, the production of biofuels such as palm oil in Colombia and Southeast Asia and ethanol from sugarcane in Brazil is causing considerable ecological, social, and human rights problems in these countries and regions. The combustion of cereals is problematical too, as long as people go hungry.

Water power has been used as a renewable energy since ancient times dating back to the ancient Greeks and Romans. Water mills, powered by running water in creeks and small rivers, have ground grain, lifted weights, cut stone, and driven mechanical, iron-forging hammers. The few water mills left are mostly used for electricity generation. Water power is provided by the Sun. About one fourth of the solar irradiation absorbed by Earth evaporates water, mostly in the warm oceans. The water vapor condenses in clouds. Clouds sail over the land and drop their water as rain, filling creeks, streams, and reservoirs of water power plants. When the water rushes down

the tubes from a reservoir to the water turbines at the foot of the dam, the potential energy of the water in the reservoir is converted into the kinetic energy that drives the electricity-generating turbine wheels. The global capacity of hydroelectricity generation was 650 $GW_{electric}$ in 1995 and provided 2,560 terawatt-hours (TWh) in that year. It grew to about 710 $GW_{electric}$ in 2005, covering nearly 20% of global electricity demand, and accounting for more than 60% of electricity from renewable sources. It is estimated that by 2050 it should be possible to obtain 4,000–6,000 TWh of electric energy per year from water power globally [36]. However, expansion of water power means building huge dams in remote mountains, or flooding large areas of rain forests, or dislocating people from the banks of big rivers. The associated financial, social, and environmental costs are high.

Ocean thermal energy conversion and tidal power stations also generate electricity with the help of water, although on a much smaller scale than conventional hydroelectric power plants. Ocean thermal energy conversion uses solar energy stored in the oceans by operating a heat engine between the warm surface water (at about 15°C) and the cold water (at about 5°C) in greater depths of the oceans. The energy source of tidal power is not sunshine but rather gravitational and rotational energy of the Earth–Moon–Sun system.

Wind originates from rising warm air and from the condensation of water vapor to form clouds. Its kinetic energy, which is only a small percentage of the solar radiation received by Earth, has been used by windmills for 2000 years in China and the Middle East, and for 800 years in Europe [36]. In the early eighteenth century about 250,000 windmills operated in Europe, grinding grain, draining the land, and performing other mechanical work. However, by the end of the eighteenth century, windmills had been ousted by the coal-fired steam engine. Since the 1990s they have come back as low-emission, high-technology electricity generators. For instance, in Germany, the number of windmills and their generating capacity grew from about 1,000 and 110 MW in 1991 to about 20,000 and 22,250 MW in 2007 [37], thanks to the economic incentives of a feed-in tariff system established by legislation.[15] In 2006, the contribution of wind power to German electricity generation from an installed wind power capacity of 20,622 MW was 30.5 TWh, or 3.5% of the total. In the same year, global installed wind power capacity was 75 GW, of which Germany contributed 20.6 GW (a share of 27.5%), and Spain and the USA both contributed 12 GW (15.6% each) [38]. By 2009 global installed wind power capacity had grown to 158 GW, with 35.2 GW in the USA, 25.8 GW in Germany, and 25.1 GW in China [39]. Estimates of the global technical potential of wind power vary between 3,000 TWh/year [36] and more than ten times that [40].

Low-temperature solar heat is provided by thermal collectors that convert sunshine into the heat of water or another working fluid, often containing an antifreeze mix. In their simplest form they are uncovered plastic absorbers that warm swimming pools. Flat-plate collectors within insulating, transparent boxes are widely used to supply warm water and heat to buildings. Vacuum tube collectors

[15] *Erneuerbare Energien Gesetz* ("Renewable Energy Law").

achieve higher temperatures and efficiencies. They are especially well suited for colder climates. Normally, flat-plate and vacuum-tube collectors are installed on roofs and are combined with water tanks for daily, weekly, or seasonal storage of solar heat. Optimum integration into the total heating system is important for maximum efficiency. For instance, analysis of a Bavarian pilot project – a district heating system for 100 well-insulated housing units with an annual total heat demand of 616 MWh – yielded the following results for flat-plate collectors: collector areas between 1 and 2.5 m^2/(MWh annual heat demand) and water storage volumes between 1.2 and 4.2 $m^3/(m^2$ collector area) can cover 32–95% of the total heat demand [41]. Satisfying the total German heat demand for room heating and warm water, which was 700×10^9 kWh in 1995, would require a collector area of about 2,000 km^2 and seasonal heat stores with a total water-equivalent volume of about $14 \times 10^9\,m^3$. It is possible to halve German room-heating demand by appropriate thermal insulation of buildings. Then, 1,200-km^2 collector area and $8{\times}10^9$-m^3 storage volume would be sufficient to provide all Germans with warm rooms and warm water via solar heat [36].

Photovoltaic electricity is generated by solar cells. Solar cells are made from semiconductors doped with tiny amounts of impurities that act as donors and acceptors. Doping works as in the field-effect transistor described in Sect. 2.3.2. Donors in the n-type region of the semiconductor produce electrons (negatively charged particles) in the conduction band, and acceptors in the p-type region produce positively charged holes in the valence band of the semiconductor. One has a p–n junction, in principle. Diffusion currents, driven by concentration differences, transport electrons from the n-type into the p-type region and transport holes from the p-type into the n-type region. This creates an internal electric field in and a potential drop across the interface layer between the two regions. When the potential drop has finally reached what is called the "diffusion voltage" $\mathscr{V}_d$, the diffusion currents vanish. Then the interface layer, also called the "space charge layer," is depleted of mobile carriers. Because of the internal electric field, the p–n junction is a diode, where current can only flow in one direction across the junction. If light quanta are absorbed by the solar cell, free, energy-rich electron–hole pairs generated in the space charge layer are separated immediately by the internal electric field. Electrons move into the n-type region and holes move into the p-type region. The p-type region is charged positively and the n-type region is charged negatively. The diffusion voltage is reduced, and a photovoltage $\mathscr{V}_p < \mathscr{V}_d$ develops between the ends of the diode. When the solar cell is connected to an external resistor, the photovoltage drives electric currents through the circuit, and electric work is performed.

Silicon in monocrystalline, multicrystalline, and amorphous forms is the most widely used base material of most solar cells. Gallium arsenide and cadmium sulfide are alternatives. The efficiency of converting sunlight into electricity is 12–15% in commercial solar cells. High-efficiency ultrathin solar cells have an efficiency of more than 20%. "If photovoltaic systems are to be able to compete with fossil fuels to generate electricity in the future, swift action need to be taken to make them not only steadily cheaper, but also more efficient. The mid-term aim is to go below

1 euros/W_p (W_p = generating capacity at peak power, in W) using silicon technology, and the long-term aim is to go below 0.5 euros/Wp with the aid of new solar technologies. Solar cells made from thin crystalline silicon on a substrate present great potential for reducing costs. This technology combines the high efficiency of thick film technologies with the cost advantages of thin films. The greatest potential for saving costs lies in printed photovoltaic (PV) technologies, in particular, organic solar cells, which currently have an efficiency of just under 8%" [42].

An array of many solar cells is a photovoltaic module. Each module typically has an area of 1 m^2. Commercial modules provide between 50 and 200 W in full sunshine under standard conditions (solar insolation about 1 kW/m^2). Photovoltaic modules can be assembled in arbitrarily large areas, fields, and installations. This flexibility is a characteristic and decisive advantage for the evolution of photovoltaics. Between 1993 and 2009 globally installed photovoltaic capacity grew by a factor of more than 400, namely, from 56 MW_p to 5,500 MW_p in 2005 [43] and 23,000 MW_p in 2009 [44]. The latter was about 0.57% of total electricity-generating capacity in 2006. Total installed photovoltaic power in Germany was about 2,500 MW_p in 2006 [45], and it had grown to 9,800 MW_p by the end of 2009 [44].[16] Germany is the major photovoltaic market worldwide, thanks to the "Renewable Energy Law," and China floods the German market with photovoltaic modules. The area required for photovoltaics was estimated in 1997 [36]: 800 km^2 of roof area is available for solar collectors in Germany; if one were to cover 100 km^2 by photovoltaic modules, thus installing a generating capacity of 10,000 MW_p, one could generate about 10 TWh of electric energy per year. This would be 1.6% of the 617.5 TWh of electric energy consumed in Germany in 2007.[17]

Solar thermal electricity is generated by mirrors that focus sunlight on an absorber. The absorber converts the sunlight into heat. The heat is transferred to a vapor or gas medium, which drives a generator. At a given generating capacity, the area of the expensive mirrors increases with the daily and seasonal variations of sunshine duration. Therefore, appropriate locations of solar thermal power plants are only in regions between 40°N and 40°S. The efficiency of solar thermal conversion of sunlight into electricity is between 20% and 35%. Therefore, one needs mirror areas of 3–5 m^2/(kW of electricity-generating capacity) during the times when solar energy flow is maximum and is about 1 kW/m^2.

Solar thermal power plants differ in the arrangement of the focusing mirrors. Parabolic troughs focus the light two-dimensionally on pipes containing the heat-transporting medium. In solar tower power plants a field of up to 1,000 mirrors, called heliostats, focuses the sunlight three-dimensionally on an absorber on the top of the tower. Paraboloid dishes with Stirling engines as generators serve as decentralized (mobile) power stations. Installed world capacity of solar thermal power plants was 354 MW in 2005 [43].

[16]International Energy Agency.

[17]Industriegewerkschaft Bergbau, Chemie, Energie, "Brancheninfo: Elektrizitätswirtschaft, Fakten und Daten zur deutschen Elektrizitätswirtschaft 2007 und Ausblick."

Geothermal energy supplied less than 1% of the world's 2008 energy demand,[18] but estimates of the technical potential go as far as 100% for hundreds of years.[19] On the other hand, a 1997 estimate of the global technical potential of geothermal energy that might be exploited within the next couple of decades was 1 EJ, at maximum [36]. The 2008 lead study of the German Ministry of Environmental Affairs (BMU) estimated that 1.8 TWh electricity and 8.2 TWh heat might be produced by German geothermal installations by the year 2020. The numerous studies of seismicity induced by hydraulic fracture in geothermal reservoirs should be continued in order to assess the risks associated with the extraction of large quantities of heat from the Earth.

2.5.3.3 Energy Payback Times, Harvest Factors, and Energy Return on Investment

An important aspect when estimating the technological potentials of renewables is the energy required for their production. This energy will be mostly taken from the energy sources presently available. The energetic payback time and the related harvest factor are relative measures of the quantity of energy that has to be used to produce the installations that exploit a renewable energy source. The energetic payback time says how long a system needs until it has supplied as much energy as was needed for its construction. The harvest factor is the total amount of energy supplied by the system during its average lifetime divided by the amount of energy required for the system's production. Typical numbers [46] are:

- Wind power plants

  Lifetime: 20 years
  Average wind speed 4 m/s: payback time 7–22 months; harvest factor 11–36
  Average wind speed 5.5 m/s: payback time 4–11 months; harvest factor 21–63
  Average wind speed 7 m/s: payback time 2–7 months; harvest factor 31–93

- Solar thermal collector for warm water supply

  Lifetime: 20 years
  Substitution of an average heating system and 56% solar supply rate: payback time 5 months; harvest factor: 48
  Substitution of a gas-fired condensing boiler and 78% solar supply rate: payback time 30 months; harvest factor 8

- Photovoltaic electricity generation

  Lifetime of silicon solar cells: 30 years

[18] 2008 IEA Key World Energy Statistics.

[19] "The Future of Geothermal Energy", Massachusetts Institute of Technology 2006; http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf.

Monocrystalline silicon, efficiency 14.5–15.5%: payback time 48–75 months; harvest factor 4.8–7.4
Polycrystalline silicon, efficiency 12–14%: payback time 25–57 months; harvest factor 6.2–14
Amorphous silicon, efficiency not available: payback time 17–41 months; harvest factor 8.6–21

Energetic payback times and harvest factors of the various forms of biomass depend on how and where biomass is being produced. Estimates are controversial and go down to small numbers, especially with respect to palm oil production.

A concept that should be included in all estimates of how things change with alterations of the energy supply system is the energy return on investment (EROI) [47]. ("Investment" means "invested energy.") EROI is the ratio of the energy that is provided by a process to the energy that is used directly and indirectly in that process. "If the EROI of a fuel is high, then only a small fraction of the energy produced is required to maintain production, and the majority of that energy produced can be used to run the general economy. On the other hand, if the EROI is very low, . . . very little net energy is available to do useful economic work. High EROI fuels are vital to economic growth and productivity" [48].

When process chains are analyzed it is important to use the same order of energy analysis at each step and define system boundaries precisely.[20] If this is done properly, the EROI concept allows comparison of nonrenewable and renewable energy sources and conversion technologies. Table 2.8 shows EROIs for a number of processes and different steps of the process chain. The differences between the minimum EROI and the maximum EROI are partly due to different system boundaries, and partly they are due to the spread in process efficiencies at each level.

The numbers of energy units gained from one energy unit invested in extracting fossil fuels from their natural deposits decline as the easily accessible oil and gas fields are being depleted. In [48] it is estimated that, on the global average, the EROI of oil at the wellhead was roughly 26:1 in 1992, increased to 35:1 in 1999, and then decreased to 18:1 in 2006. Furthermore, according to Table 2.8 and [49], the energy returns from energy invested in collecting renewables from their natural flows are substantially below those of exploiting oil and gas wells in the twentieth century.

[20]Where to draw the system boundaries properly is sometimes controversial. For instance, there are people who argue that photovoltaic cells will never reproduce the energy invested in their production, because in this energy one should include the fuel used by workers in factories producing photovoltaic cells, and during boat-trip vacations in the Caribbean, for example. Arguments of this quality are perhaps responsible for the persisting rumors that the harvest factors of photovoltaic cells and even wind power installations are less than 1.

Table 2.8 Energy return on investment (*EROI*) for energy carriers and steps of process chains. *CCS* carbon (dioxide) capture and storage, *POU* point of use. (Source: Hannes Kunz, Institute of Integrated Economic Research, http://www.iier.ch)

	EROI (min)	EROI (avg)	EROI (max)
Coal			
Mine mouth	50	70	90
Coal to plant	45	65	86
Coal to electricity	14	28	43
Electricity from coal after CCS	4	14	24
Oil			
Well	12	56	100
Transportation of crude	10	52	95
Refinement	8	49	90
Gasoline/diesel at pump	7	44	81
Industrial fuels at POU	7	47	86
Direct heating from oil at POU	5	43	80
Natural gas			
Well	30	40	50
Pipeline/truck to power plant	24	36	48
Gas to electricity	7	17	26
Direct heating from gas at POU	18	29	40
Nuclear			
Mine	30	115	200
Enrichment	12	91	170
Power plant	4	36	68
Solar			
Electricity from photovoltaics	4	8	12
Electricity from solar concentration	4	7	10
Autonomous solar use (with battery)	1	3	5
Direct solar thermal energy (warm water)	30	40	50
Direct solar thermal energy (heating)	5	8	10
Wind			
Electricity from wind	10	18	25
Autonomous wind use (with battery)	3	8	13
Wind to grid	7	15	23

2.5.4 Energy Conservation

Grand-scale use of renewable energies requires large investments and big areas. Integration of renewables into the existing energy systems at minimum cost calls for careful system analysis. The study *Long-Term Integration of Renewable Energy Sources into the European Energy System* has looked into scenarios of phasing out fossil and nuclear energies by 2050 in Europe, replacing them by renewables in combination with energy conservation measures. The latter are supposed to reduce

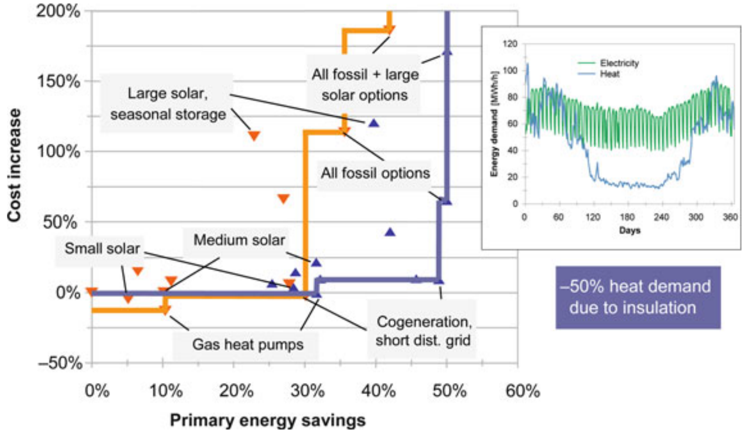


Fig. 2.11 Energy savings and cost increases for satisfying the fluctuating electricity and heat demand of "Würzburg." *Upright triangles* are are for 50% reduction of room heat demand by thermal insulation of buildings; *inverted triangles* are for 0% reduction of room heat demand. The *inset* shows the weekly fluctuations of the average daily electricity demand (MW) (*upper curve*) and the seasonal change of heat demand (MW) (*lower curve*). *CHP* combined heat and power (Source: Thomas Bruckner, University of Leipzig)

energy demand by more than 50%. "However . . . the future cost figures do not include efficiency measures which involve substantial restructuring of the economy and could, thus, not be calculated for this book" [50], so the cost estimates in this study only refer to renewables.

Smaller, less complex systems such as cities allow computation of all costs for optimized technology combinations. Since the potentials of energy conservation and renewables do not add up, but are interdependent in not-at-all obvious ways, advanced system-analytical tools are required to find out how deeply, and at what costs, they can be exhausted under given climatic conditions and energy demand profiles. Thermoeconomics provides the basic analytical and conceptual framework [51]. One such tool is the *d*ynamic *e*nergy *e*mission and *c*ost *o*ptimization model *deeco*. To illustrate competition and synergy between energy technologies when restructuring an energy system, and to compute the associated costs as well, it has been applied to the model city of "Würzburg" [52]. This model city has the fluctuating room-heating and electricity demand shown in Fig. 2.11. These demands, and sunshine and temperature variations as well, were measured for the real city of Würzburg during a representative year. This city of about 135,000 inhabitants is located in central Germany on 50°N latitude. Reductions of energy consumption and emissions, and the associated cost reductions/increases, were computed for a number of scenarios that combine energy-saving and solar-heating technologies.

The specific costs of all technologies comprise annuities of investments as well as operation and maintenance costs. The total cost of an energy conversion technology is calculated by multiplying the specific cost with the maximum capacity

of the technology needed according to the optimization results. The total cost of the optimized energy system is calculated as the sum of the costs of all energy conversion and transportation technologies, plus the cost of fuel and the cost of the electricity imported from the national grid.

In the reference scenario all heat is supplied by oil boilers, and all electricity comes from the national grid. Energy prices are those of the mid-1990s. The energy supply technologies are grouped in scenarios. Each scenario contains a subset from the following technologies, in addition to those of the reference scenario: gas-fired (conventional and condensing value) boilers, small and medium-sized gas-fired cogeneration (combined heat and power) units, district heat from a large coal-fired cogeneration plant with back-pressure turbine, gas-fired ambient air heat pumps, solar heating systems of small, medium, and large size, combined with daily, weekly, and seasonal heat storage, covering 7%, 25%, and 79% of total heat demand, respectively. Appropriate conversion efficiencies are used for each technology.

Vector optimization with respect to primary energy consumption, emissions,[21] and cost was done for a great number of scenarios. An overall picture of trade-offs between primary energy savings and cost increase for various technology combinations is shown in Fig. 2.11. More detailed results for some characteristic scenarios (identified by the names given in [52]) are as follows[22]:

1. In the scenario *MCogen*, medium-sized cogeneration units, feeding short-range district grids, cover 57% of the heat demand and 86% of the electricity demand. The remaining 43% of the heat demand is contributed by gas-fired boilers. Thirty percent of the primary energy used in the reference scenario is saved and costs are reduced by 2%.
2. In the scenario *AllNonSolar*, it is possible to choose among all non-solar-energy technologies during optimization. In this case, small and medium-sized cogeneration units supply 73% of heat and 86% of electricity, whereas gas-fired condensing value boilers meet nearly all of the remaining heat demand. Nevertheless, the resulting energy savings of 36% are only 6% points higher than in *MCogen* and, thus, much less than the sum of the individual savings potentials of the technologies considered. Furthermore, the small additional savings are bought with a cost increase of 114% with respect to the reference scenario. This example shows how aggregated savings potentials cannot be fully realized owing to the competition between different technologies. The investment costs are spent for all technologies, but many contribute only little to savings.
3. In the scenario *All + Solar*, large solar-thermal installations, including seasonal heat storage, are available in addition to all energy conservation technologies. Here 48% of the heat is contributed by solar installations and 39% by cogeneration. The latter also meets 47% of electricity demand, the rest of which is covered by imports from the grid. Primary energy savings increase to 42%,

[21] CO_2, NO_x, SO_2, and dust.

[22] Emission reductions roughly follow energy savings.

but costs rise by 186% compared with the reference case. Again, competition between technologies shrinks the total primary energy conservation potential and drives up costs.

The maximum energy savings at a given cost increase without additional heat insulation are reached for those scenarios (not all identified here) that are placed near the left trade-off plot in Fig. 2.11. Additional thermal insulation of buildings increases potential energy savings substantially in almost all scenarios, whereas cost increases remain moderate, as shown by the right trade-off plot. A further finding, not shown in Fig. 2.11, is that a combined energy and carbon dioxide tax of US $30 per barrel of oil equivalent, as applied in the 1993 IEA CO_2 tax scenario [53], would reduce relative cost increases in the scenarios *AllNonSolar* and *All + Solar* by about 50% and lower the cost of the *MCogen* scenario by more than 10% below the cost of the reference scenario [52].

The special-case analyses for "Würzburg" show that care has to be taken when estimating potentials and costs of integrating energy conservation with renewable energy utilization. One needs detailed information on energy demand and climate in the system considered, appropriate modeling of technology interactions, and dynamic optimization techniques.

The thermodynamic limits of energy conservation are easier to compute, because one is entitled to use all physically thinkable, although technically extremely idealized, simplifying assumptions for this exercise. The limits have been estimated for the industrial energy demand of The Netherlands, Germany, Japan, and the USA by thermoeconomic optimization [30,31]. The Simplex algorithm yields, at best, the possibility of saving 50% of primary energy, with unchanged energy services, for system-integrated heat exchanger networks, heat pumps, and cogeneration plants. Vector optimization with respect to primary energy and cost indicates that energy and cost minimization become parallel objectives only at energy prices that are 3–4 times higher than those in the 1980s. It turns out that the given exergy demand structures of the production processes in the countries considered determine the maximum potentials of energy conservation. Improvements in energy efficiency are limited by basic thermodynamics to factors that do not exceed 2.

2.6 Technological Perspectives

Exploitation of the great potentials of wind power, photovoltaics, and solar heat in northern industrial countries is handicapped by fluctuations of wind and sunshine. Occasionally, so much wind power is fed into the German grid that overload can only be avoided by paying neighboring countries to take the surplus electricity.[23]

[23]The law (*Erneuerbare Energien Gesetz*) that stimulates the enormous growth of wind power and photovoltaics entitles windmill owners to feed their electricity into the grid at guaranteed feed-in tariffs, no matter whether the grid can take it or not.

Therefore, progress in storing electricity (and heat) is decisive for expanding the use of fluctuating renewable sources. Fission, fusion, and solar farms in deserts and in space are not handicapped by stochastic fluctuations. Of course, they have other problems.

> Experience shows that problems with and public opposition to an energy technology grow with the quantity of energy this technology provides.

2.6.1 *Fission*

The controlled fission of uranium and thorium in nuclear reactors is so far the only peaceful method for converting mass m into energy E according to Einstein's equation $E = mc^2$. Here m is the difference between the mass of the uranium-235 (^{235}U) nucleus and the smaller sum of the masses of the fission fragments into which the ^{235}U nucleus decays after having absorbed a thermal neutron. Fission can only be produced by thermal neutrons, which move so slowly that their kinetic energy is of the order of $k_B T$. However, the neutrons that are part of the fission fragments, and whose number must exceed 1 in order to maintain a chain reaction, are very fast. They must be slowed down by a moderator. Water and graphite are the moderators used in existing nuclear power plants.

In water-moderated reactors the water also serves as the coolant, from which the steam is produced that drives the steam turbine. Pumps circulate the cooling water so that it can transport the heat away from the fuel rods in the reactor core. In the case of an accidental breakdown of the cooling system, the core heats up, and vapor bubbles form in the boiling water. Since the density of water in the vapor bubbles is very low, neutron moderation weakens. The fast neutrons are no longer slowed down in sufficient quantities, and the chain reaction comes to an end. One says that the reactor has a negative temperature (void) coefficient. Nevertheless, in the worst-case scenario the heat that is generated in the fuel rods by β decay, for hours or even days after reactor shutdown, may cause a core meltdown. A partial core meltdown occurred during the Three Mile Island reactor accident near Harrisburg, USA, in 1979. On March 11, 2011, after an earthquake of strength $M\_w = 9$ in the Tohoku region of Japan and the follow-up tsunami that destroyed the cooling systems in several of the Fukushima-Daiichi nuclear power plants, core meltdowns occurred in 3 reactors, and large quantities of radioactivity were released. More than 100,000 people had to be evacuated, probably permanently. After this accident opposition to nuclear power increased. The German government made a U-turn in its energy policy. Only 8 months before the Fukushima accident it had extended the legal operation time for German nuclear power plants substantially. But on

May 30, 2011, it was decided to shut down the last German nuclear reactor in the year 2022. Plans are now to replace nuclear and coal power plants with large windparks in the North Sea in combination with high-power transmission lines and gas-fired power stations, with photovoltaics, and with storage facilities for the fluctuating energy from wind and sunshine. In the preceding discussions one cabinet member was asked how to finance the necessary huge investments without too much cost for electricity consumers and the tax payer. He replied: “More competition in the energy market will take care of that.”

Graphite is the moderator in RBMK reactors, which were developed and installed in the Soviet Union and some of its satellite states. The fuel rods are imbedded in the moderating graphite. Cooling is by water. In contrast to water-moderated reactors, RBMK reactors have a positive temperature (or void) coefficient. This is because water also absorbs neutrons, and the reactor has to be designed correspondingly. If the reactor’s cooling system fails, the graphite and the cooling water heat up, and water evaporates. In this case the very low water density in vapor *reduces* neutron absorption drastically, whereas moderation by graphite continues. This dramatically alters the balance of thermal neutron production, causing a runaway condition, in which more and more thermal neutrons accelerate the chain reaction. If this is not stopped by neutron-absorbing control rods, the core melts down. This happened on April 26, 1986, at reactor 4 of the Chernobyl power plant close to Kiev, when, in a badly organized safety experiment, the positive temperature coefficient, in combination with deliberately broken safety rules by insufficiently trained operators, produced the worst nuclear power plant disaster before the Fukushima disaster.

Since then nuclear power has been seen by many people as an energy option with intolerable risks. This is at least the situation in many wealthy industrial nations, which have not suffered from energy scarcity for several decades. Things are different elsewhere. For instance, there were still 12 RBMK reactors operational in 2009, despite their positive temperature coefficient, although with improved safety features: one in Lithuania and 11 in Russia. The Lithunian reactor was shut down at the beginning of the year 2010.

The other argument raised against nuclear energy is that nuclear-power-using societies have not yet agreed on appropriate sites for safe, long-time disposal of burned-out nuclear fuel rods. The problem is that spent fuel from nuclear reactors still contains considerable amounts of ^{235}U. In addition, significant amounts of plutonium-239 (^{239}Pu) are generated during fission.

Disposal of long-lived radioactive waste in solid rock is an option that comes close to what nature did when it accumulated natural uranium in sites such as the granite rock formations of the Black Forest in southwest Germany [25]. One would have to enclose the radioactive waste in appropriate containers, insert these containers in holes, deeply drilled into the rock, and completely fill all remaining voids at the disposal site with water-impermeable material. This option has not yet been realized by any of the nuclear-energy-using countries. One reason may be the associated cost. It is estimated to be between 2 and 3 euro cents per kilowatt-hour of electricity from nuclear power stations [25]. Presently, German utilities,

generating electricity from nuclear power, are legally obliged to hold 0.5 euro cents per kilowatt-hour electricity in reserve for the disposal of radioactive waste and the decommissioning of nuclear power plants.

The energy requirements for removing burned-out nuclear fuel rods from the biosphere by accelerating them to escape velocity via electromagnetic mass drivers or rockets [54] and the resulting waste heat burden on the environment, are calculated in Sect. 3.6.3.

Reprocessing plants can separate ^{235}U and ^{239}Pu from the other components of spent fuel. This would significantly address two major concerns, in principle. It would greatly reduce the long-lived radioactivity of the residue, and it provides purified ^{235}U and ^{239}Pu as reactor fuel. Using uranium in fast breeder reactors, cooled by liquid metals such as sodium, would have similar benefits. But both technologies have raised considerable safety and environmental concerns and are used in a few countries only. Especially in France, where nuclear power covers more than 70% of electricity demand, people value nuclear risks much lower than people in most other west European countries.

Pebble bed high-temperature reactors are an alternative to water-moderated and RBMK reactors. Since their safety and waste-disposal risks are much lower than those of the other reactor types, they represent an option for what some people call "green" fission. These reactors use thorium besides ^{235}U as a nuclear fuel. Although not fissile itself, thorium-232 (^{232}Th) will absorb slow neutrons to produce uranium-233 (^{233}U), which is fissile (and long-lived). Hence, it is fertile, like uranium-238 (^{238}U). In one significant aspect ^{233}U is better than ^{235}U and ^{239}Pu, because of its higher neutron yield per neutron absorbed. Utilizing thorium as a nuclear fuel has the advantage that it is more abundant in Earth's crust than uranium. Also, all of the mined thorium is potentially usable in a reactor, as compared with 0.7% of natural uranium. Thus, about 40 times the amount of energy per unit mass might theoretically be available, without recourse to fast breeder reactors. Global total thorium resources are estimated to be about 2.5×10^6 t [55].

Thorium was used as a fuel in the first thorium high-temperature reactor (THTR-300), which was developed in Germany. It was a pebble bed reactor, where the nuclear fuel is enclosed in spherical fuel elements called "pebbles." The reactor core contained approximately 670,000 pebbles. These tennis-ball-sized pebbles are made of pyrolytic graphite (which acts as the moderator), and they contain thousands of microscopic fuel particles. These microscopic fuel particles consist of a fissile material (such as thorium and uranium) surrounded by a coated ceramic layer of silicon carbide (SiC) for structural integrity. The durability of the ceramic enclosure of the radioactive material after removal from the reactor is estimated to be at least one billion years. Thus, storing radioactive waste from pebble bed reactors is less problematical than storing nuclear fuel rods from conventional water-cooled reactors. Furthermore, in the case of a terrorist attack, e.g., by a rocket, the fuel elements would fly apart and suffer (and do) much less damage than scattered fuel rods, because the microscopic fuel particles are extremely hardened by the SiC coating. Pebble bed reactors are cooled by convection (i.e., natural circulation) of inert or semi-inert gases such as helium, nitrogen, or carbon dioxide. Because of

their passive safety and their negative temperature coefficient – if the temperature in the pebble bed reactor goes up, the reaction rate goes down – a core meltdown, due to the breakdown of an active cooling system, is impossible.

The official history of the THTR-300, as told by the Web-based encyclopedia Wikipedia and other sources, goes like this. The THTR-300 was a thorium high-temperature nuclear reactor rated at 300 $MW_{electric}$ (THTR-300). The German state of North Rhine–Westphalia and Hochtemperatur-Kernkraftwerk financed construction of the THTR-300. Operations started on the plant in Hamm-Uentrop, Germany, in 1983, and it was shut down on September 1, 1989. The reactor was synchronized to the grid for the first time in 1985 and started full-power operation in February 1987. The THTR-300 cost 2.05 billion euros and is expected in 2011 to cost an additional 1 billion euros in decommissioning and other associated costs. On September 1, 1989, the THTR-300 was deactivated because of its cost and increased public scrutiny following both the Chernobyl accident and the THTR-300 fuel pellet event of May 4, 1985, in which a fuel pellet became lodged in a fuel feed pipe to the core. On October 10, 1991, the 180-m-high dry cooling tower, which at one time was the highest cooling tower in the world, was explosively dismantled, and from October 22, 1993 to April 1995 the remaining plant was decommissioned. The THTR-300 technology was sold to China in 1991. Safe enclosure, including the prestressed-concrete reactor vessel, was finished in September 1996 [56].

The high-temperature reactor technology is being developed further by MIT, the South African company PBMR, General Atomics (USA), the Dutch company Romawa, Adams Atomic Engines, Idaho National Laboratory, and the Chinese company Huaneng. In June 2004, it was announced that a new pebble bed reactor would be built at Koeberg, South Africa, by Eskom, the government-owned electric utility. But on September 17, 2010 the South African Minister of Public Enterprises announced the closure of the PBMR.

The unofficial story of why Germany gave up the most advanced and safest nuclear technology, developed at high cost to the taxpayer, was given in a private communication from Hermann Josef Werhan. Werhan belongs to a prestigious German industrial dynasty and is a son-in-law of Konrad Adenauer, the first chancellor of the Federal Republic of Germany. In the late 1990s we met accidentally at breakfast in a Berlin hotel, discovered that we had been at different energy meetings the evening before, and started talking energy business. Werhan opened his wallet and showed me two photographs, side by side: "This is my wife, and that is Rudolf Schulten of Forschungszentrum Jülich, who developed the pebble bed reactor." When I responded,"What a pity that Germany gave up this technology," he asked me, "And do you know why?" I told what I knew from the press: "After the Hamm-Uentrop prototype had started operations, the government asked the utilities to finance further development of the reactor to full market maturity, because enough taxpayer's money had gone into the prototype development. But the big power companies refused to do so, because they had already water-moderated reactors developed and running and were afraid of the financial risks of further THTR development." Werhahn laughed. Then he told me his insider story. He had been present at the board meetings of one of the big German utilities when the

decisions against the THTR-300 were taken. According to Werhahn, the real reason for killing this innovative technology was that safe, small-scale high-temperature reactors could be operated even by small municipal utilities right within the cities, producing electricity and heat in a very decentralized way. This was against the commercial interests of the big utilities, who wanted to dominate the market with large, centralized power stations, including water-moderated nuclear reactors in the 1,000-$MW_{electric}$ range.[24]

Werhahn keeps advocating pebble bed reactors. Because of their safety features and the billion-year enclosure time of the radioactive particles by the SiC coatings, he calls them with some justness "green" fission reactors. In fact, Edward Teller, the "father of the fusion bomb," had a reactor with the properties of the high-temperature reactor in mind when he commented at the 1955 United Nations conference in Geneva on the peaceful use of nuclear energy in the following sense. "The aim of a peaceful use of nuclear energy for world-wide electricity generation requires the development of completely new nuclear power stations – free from the risk of an accident that releases large quantities of radioactivity. Only when such risk-free power stations will be available the people of our countries will accept the peaceful use of nuclear energy in the long run" [25].

2.6.2 Fusion

Solar fusion of hydrogen to helium described in Sect. 2.2 has an extremely small overall reaction rate. Nevertheless, the gravity of the huge solar mass of 2×10^{27} t holds the solar protons and electrons together long enough for sufficient reactions to occur and compresses them to a plasma whose density exceeds that of water by a factor 150 in the solar core. Fusion occurs in this spherical core of radius 140,000 km at temperatures of 10×10^6–15×10^6 K and pressures of about 10×10^9 atm. The resulting power is 300 W/m^3 of plasma.

Fusion has occurred on Earth in hydrogen bomb detonations, so far. In thermonuclear weapons the energy of a fission bomb is used to compress and heat the fusion fuel, which consists of the hydrogen isotopes deuterium and tritium, or lithium deuteride. No thermonuclear weapon has been used in warfare. The last time scientists set off a hydrogen bomb was in 1991 under the Nevada desert. It is hoped that thermonuclear detonations will never again occur under any circumstances.

Research into controlled fusion for electricity generation has been going on since the early 1950s. Lacking gravitational assistance in producing high plasma densities, one has to find ways that differ from that of the Sun and stars.

One method tries to confine an extremely hot plasma of very low density in a magnetic bottle for sufficiently long times so that fusion reactions can occur. Promising parameters are as follows: plasma temperature 150×10^6–200×10^6 K,

[24] In fact, 20 years later, Germany is the country with the highest electricity prices in Europe.

density 4×10^{-9} g/cm^3, pressure 6 atm, confinement time 1–1,000 s. The expected fusion power is 2 MW/m^3. Different from the Sun, terrestrial fusion fuel is not simply hydrogen (H), but is a mix of the heavier hydrogen isotopes deuterium (D) and tritium (T). The reaction

$$\mathrm{D} + \mathrm{T} \rightarrow^{4} \mathrm{He} + \mathrm{n} + 2.8 \times 10^{-12}\,\mathrm{W\,s}$$

generates neutrons (n), which transport useful heat. They also produce fresh fuel supply, radiation damage, and radioactivity.[25] The ^{4}He nuclei (α particles) heat up the plasma to the temperatures needed for self-supporting fusion.

Another way to achieve fusion is inertial confinement by energy-rich laser or particle beams. These beams are directed on a pellet that usually contains a mixture of deuterium and tritium. Shock waves from the exploding outer layer of the pellet compress the remainder of the target within extremely short times of a few nanoseconds into the extremely high plasma density of about 200 g/cm^3. The plasma heats up to about 100×10^6 K. At a frequency of 20 implosions per second, one expects a thermal fusion power of about 2 MW/(m^3 of reaction volume) [36].

Stellerators and tokamaks are machines that can confine fusion plasmas magnetically. Plasma is confined in a stellerator by ring-shaped, twisted magnetic field lines, produced by a current-carrying coil of quite complicated geometry. A stellerator could operate continuously. "Wendelstein 7-X," the largest stellerator under development at Greifswald, Germany, is supposed to test whether the stellerator principle is suitable for power stations. Initial plasma heating to fusion temperatures has to be done by an outside source. A tokamak produces a toroidal magnetic field for confining the plasma. Initial heating to fusion temperatures is done by inducing electric currents in the plasma. This is a pulsed process. The international ITER project, the largest fusion experiment worldwide, is building a tokamak in Cadarache, France. The projected technical data are as follows: total radius 10.7 m, overall height 30 m, plasma radius 6.2 m, plasma volume 837 m^3, plasma mass 0.5 g, magnetic field 5.3 T, maximum plasma current 15×10^6 A, heating power and current operation 73 MW, fusion power 500 MW, energy enhancement factor 10, average plasma temperature 100×10^6 K, duration of burning more than 400 s. Construction costs were estimated at €5 billion in 2001, and the operation cost was estimated at €265 million annually during the projected 20 years of testing.[26]

The biggest problem with controlled fusion is material stability under neutron irradiation. One does not expect to have the first fusion reactor that supplies

[25] Häfele et al. [57] estimated that fusion reactors will produce about as much radioactive waste as fast breeder reactors. However, the radioactivity of the confinement material, which must be replaced periodically because of damage by neutron bombardment, dies off much more rapidly than the radioactivity of spent fuel rods from fission reactors.

[26] Source: Max-Planck-Institut für Plasmaphysik, http://www.ipp.mpg.de/.

electricity to the public grid before 2050. Despite that, much money is spent on fusion research, because there is a practically inexhaustible supply of terrestrial fusion fuel.

The deuterium content of water is 0.1%. Thus, the oceans represent a reservoir of 5×10^{13} t deuterium. Radioactive tritium has a half-life of 12 years. It can be bred from lithium, embedded in the reactor walls, by bombardment with neutrons, which are produced in the fusion plasma. Two kilograms of lithium results in 1 kg of tritium. The 2-km-thick layer below the surface of Earth's land masses contains about 2×10^{13} t of lithium [36]. To satisfy the global electricity demand of 16,379 TWh in 2006 by fusion power stations, one would need 655 t of lithium and 197 t of deuterium annually.

2.6.3 Solar Power from Deserts and Space

2.6.3.1 Solar Thermal Power Plants in Deserts

The Deutsche Physikalische Gesellschaft (DPG; German Physical Society)[27] has analyzed the potential for growth of solar thermal power plants in Earth's sun belt between 40°N and 40°S. In its 2005 study *Climate Protection and Energy Supply in Germany 1990–2020*, the German Physical Society stated [58]: "Seen from a physical and technical point of view, there can be no doubt that solar thermal power plants in southern latitudes represent one of the best options for supplying ... large quantities of CO2-free electricity. The relevant research and development activities have been in progress for about 25 years, and have reached a stage where it is time to energetically pursue their commercialisation. The Deutsche Physikalische Gesellschaft appeals to all the parties involved – industry, energy providers and the appropriate government bodies – to do everything in their power to promote the launch of the outlined program to create a market for solar thermal power plants in Earth's equatorial sunbelt. We can justifiably hope for new inventions. Providing incentives that will encourage successful research and creating the appropriate research infrastructure must also be seen as a valuable investment towards finding solutions to global warming. ...

A promising first step would be to make solar energy available to the populations actually living in the sunbelt of Earth near the equator (North Africa, the Middle East and Central America). The process heat generated concurrently with the solar power could then be used for desalination of sea water to meet the growing demand for drinking water. Given that the people living in these regions themselves account for approximately 15% of the world's energy requirements, this in itself would go a long way towards protecting the global climate. The calculated potential electricity yield of solar thermal power plants in the regions close to the equator is tremendous,

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[27]The German Physical Society has more than 55,000 members and is the biggest physical society in the world.

far exceeding local demand. In North Africa, for example, it amounts to about 200–300 GWh_{el} per square kilometer per annum. In other words, Germany's entire electricity demand could be satisfied with a built-over surface area of $45 \times 45\,km^2$ (equivalent to 0.03% of all suitable areas in North Africa). The next step in this direction must therefore be to set up an efficient electricity network between North Africa and Europe. This can be achieved with high-voltage DC (HVDC) transmission lines of the type already in operation for transmitting electricity over distances up to several thousand kilometers. At today's prices, it would cost approximately 2.5 billion euros to build a high-voltage DC transmission line of the kind that such an electricity network would require, with a capacity of 2,000 MW and covering a distance of 3,000 km. This means that it would cost 1.5–2 cents/kWh to transfer solar power from North Africa to Central Europe. Assuming a dynamic market introduction of solar thermal power plants, from about 2015 onwards, it should be possible to attain a price level of about 10 cents/kWh for imported solar electricity in Germany. This level should ultimately drop to about 5.5 cents/kWh. . . .

These are major projects involving high investment costs and a correspondingly high financial risk which would have to be cushioned by State guarantees in view of the urgency of the climate problem. Moreover, the facilities would have to be built at the southernmost tip of Europe or in North Africa, which calls for the appropriate international contacts on the part of the electricity distributors – and possibly even at government level – providing the necessary transit arrangements. The hesitant attitude of the energy industry and the appropriate government bodies may perhaps be explained by the initial optimism of the 1990s in Germany, when we were confident of being able to cope with the CO_2 problem at home. However, the extremely slow rate at which CO_2 emissions are being reduced, as demonstrated once again in this study, should be proof enough that we urgently need to import solar power. Although a number of solar thermal projects exist at the planning stage in various parts of the world, their implementation has been postponed year after year despite promised financial support from the World Bank (Global Environmental Facility)."

Four years after this declaration of the DPG the public was surprised to learn that big international companies are considering building large solar thermal power plants in the deserts of Earth. The cost of building power plants in North Africa and HDVC transmission lines there and to Europe is estimated to be about €400 billion. The plan has the name DESERTEC. The following is a communication that announces the first formal steps toward producing solar thermal electricity for the EUMENA region, consisting of Europe, the Middle East, and North Africa.

"On the 30th of October 2009, the articles of association for the DESERTEC industrial initiative 'DII GmbH' (DII) have been signed in Munich by twelve companies and the DESERTEC Foundation. The long-term goal is to satisfy a substantial part of the energy needs of the MENA countries and meet as much as 15% of Europe's electricity demand by 2050. On 13th of July the founders already signed a Memorandum of Understanding with the aim to realise the DESERTEC Concept in the EUMENA Region. More information and the official press release can be read and downloaded . . . (from): http://www.DESERTEC.org.

DESERTEC Facts, History and Future:

(1) The DESERTEC Concept was developed since 2003 by the German Club of Rome and TREC, a network of experts around the Mediterranean (incl. His Royal Highness Prince Hassan bin Talal of Jordan, former president of the international Club of Rome).
(2) Three studies (2004–2007) under the lead of the German Aerospace Center (DLR) confirmed the feasibility of DESERTEC.
(3) In 2008 the DESERTEC Foundation has been formed to coordinate the activities of the DESERTEC networks and to create alliances to realize DESERTEC worldwide. . . .
(6) At October 1st 2008 founders of the DESERTEC Foundation convinced MunichRe to initiate jointly the DII to realise DESERTEC in the EU-MENA region. The DESERTEC industrial initiative has been by DESERTEC Foundation in cooperation with MunichRe.
(7) The group of DII founding members consists of 12 companies and the independent NGO DESERTEC Foundation. Shareholders of the DII are ABB, ABENGOA Solar, Cevital, DESERTEC Foundation, Deutsche Bank, E.ON, HSH Nordbank, MAN Solar Millennium, Munich Re, M+W Zander, RWE, SCHOTT Solar and SIEMENS. It is envisaged that further companies from different countries, preferentially from North Africa and the Middle East, will join the DII. . . .
(10) The DESERTEC Foundation plans to initiate further DIIs in other regions (e.g. USA, India, China and Australia) to achieve its mission of realising the DESERTEC Concept Clean Power from Deserts for a world with 10 billion people. . . .
(14) On the 30th of October 2009 the articles of association for the 'DII GmbH' (DII) were signed in Munich, where the headquarters of the DII will be based. Until 2012 the DII will focus on: Acceleration of implementation of the DESERTEC Concept, by creating of a favourable regulatory and legislative environment, analysis of concrete reference projects, developing of a roll-out plan for such projects, and additional or more detailed studies, where needed.
(15) Paul van Son will be the CEO of the DII . . . Mr. van Son is also Chairman of the European Federation of Energy Traders (EFET) and Chairman of the Energy4All Foundation which is active in Africa."

Nearly 40 years after the first vision of solar farms for 10 billion people, sketched in Table 2.7, plans for large-scale solar power from Earth's deserts are beginning to materialize.

2.6.3.2 Solar Power Satellites and Space Industrialization

Solar power satellites (SPS) are an alternative to terrestrial sun farms. They were first proposed and patented by Peter E. Glaser [59–62]. They are to be stationed in geosynchronous Earth orbit (GEO), always above the same point on the equator at a

maximal distance of 35,785 km. Like terrestrial sun farms and solar thermal power plants, they convert sunlight into electric energy, either directly by photovoltaic cells or by solar thermal dynamic systems such as Brayton, Rankine, or Stirling generators. Klystrons convert the electric energy into microwaves of about 3-GHz frequency, which are beamed from a phased-array transmitting antenna of the satellite to a large receiving antenna on Earth. There, the microwave energy is reconverted into electricity, which is fed into the public grid. Typical generating capacities of SPS are 5000–10,000 MW at a bus bar on Earth.

A 10,000-MW solar cell SPS, as proposed by Glaser, consists of two solar "paddles," each having an area of 60 km^2 covered with silicon or gallium arsenide photovoltaic cells. The total weight is between 34,000 and 86,000 t, depending on the construction materials.

Boeing proposed SPS using thermal electric conversion [63]: mirrors focus sunlight on cavities where a circulating gas such as helium is heated and drives heat engines that power electricity generators. A 10,000-MW SPS based on this principle has the following dimensions: length 15 km, area of the reflectors that concentrate sunlight on the gas-heating cavities 50 km^2, waste-heat radiator 1 km^2.

In both SPS versions, the diameters of the transmitting antenna of the satellite and of the receiving antenna on Earth are about 1 and 10 km, respectively.

SPS receive 4–11 times more sunlight per area than installations in the sunshine-richest regions of Earth. And this energy is almost always available. Earth overshadows a satellite in GEO during such short intervals such that satellite output is reduced by only 1%, on an annual average, compared with a satellite in permanent sunshine. The umbra of the satellite does not reach Earth. Other advantages over solar Earth-based systems are that structures can be up to 1,000-fold lighter and have a longer life, and there is need neither for collector cleaning nor for energy storage.

Since a satellite in GEO does not move relative to Earth's surface, the sharply focused microwave beam can be directed to receiving antennas that are close to large energy consumers. Thus, energy losses in long transmission lines can be avoided. Microwaves in the 3-GHz frequency range penetrate the atmosphere and clouds with small losses and are converted into electric energy by the terrestrial rectifying antenna (rectenna) with an efficiency of 90%. The maximum intensity in the center of the microwave beam is 230 W/m^2. This is comparable to the average solar energy flow on Earth, whereas the maximum solar intensity is about 1,000 W/m^2. Outside the rectenna the microwave intensity is 0.3 W/m^2. In the case of satellite perturbations, dephasing of the transmitting antenna and defocusing of the microwave beam disperses the microwaves to intensities much below that. The rectennas pose some land-use problems and are about 10% of the overall cost. There are plans to make them from a wire mesh, which absorbs most of the microwave energy but allows transmission of sunlight and water to the ground under it for sustenance of the existing flora and fauna.

Of course, the big obstacle to SPS is the unsolved problem of how to get them into GEO, and at what cost. The US Department of Energy and NASA conducted the first comprehensive studies on SPS in the 1970s. The summary of the first study,

"Satellite Power System – Concept and Evaluation Program" [64] states: "The Reference System description emphasizes technical and operational information required in support of environmental, socioeconomic, and comparative assessment studies. Supporting information has been developed according to a guideline of implementing two 5 GW SPS systems per year for 30 years beginning with an initial operational date of 2000 and with SPS's being added at the rate of two per year (10 GW/year) until 2030. . . . the Reference system concept, which features gallium–aluminum–arsenide (GaAlAs) and silicon solar cells options . . . utilizes a planar solar array (about 55 km^2) built on a graphite fiber reinforced thermoplastic structure. The silicon array uses a concentration ratio of one (no concentration), whereas the GaAlAs array uses a concentration ratio of two. A 1-km diameter phased array microwave antenna is mounted on one end. The antenna uses klystrons as power amplifiers with slotted waveguides as radiating elements. The satellite is constructed in geosynchronous orbit in a six-month period. The ground receiving stations (rectenna) are completed during the same time period. The other two mayor components of an SPS program are (1) the construction bases in space and launch and mission control bases on earth and (2) fleets of various transportation vehicles that support the construction and maintenance operations of the satellites." The final report on all studies [65] gives details on transportation and bases: 425-t single launch capacity to low Earth orbit (LEO; 200 km from Earth's surface); eight 425-t launches per week, 400/year; a 6,400-t construction base at LEO; electric propulsion (by ion or plasma engines) from LEO to GEO; Earth–GEO personnel transfers 32 times per year, 75–80 passengers per transfer; 3-month individual stay time. On the basis of this system and 1978 prices, the estimated capital investment needed to just get the system started is of the order of US $250 billion, with a cost of US $1,400 to US $7,000 per kW (electric) generating capacity. Twenty-five percent to 30% of this cost is for space transportation, 80% of which is for Earth–LEO transfer [66].

The US National Research Council and the Congressional Office of Technology Assessment examined this SPS concept and concluded that it might be technologically feasible but programmatically and economically unachievable.

An alternative transportation and production scheme was not considered in these studies, although its exploration had been supported by NASA in the mid-1970s. "The Low (Profile) Road to Space Manufacturing" [67] by Princeton physics professor *Gerard K. O'Neill* describes the construction of SPS with a minimum of materials and energy from Earth, relying mostly on energy from the Sun and materials from the Moon. It was seen as the first step in a grandiose plan for the colonization of space [68], which was further elaborated in the vision of *The High Frontier* [69].

The low profile road rests on two key technological elements: (1) the Space Shuttle, or a follow-up Earth-to-LEO transportation system, and (2) the electromagnetic mass driver. The first Space Shuttle made its first orbital test flight on April 12, 1981, and the Space Shuttle program is scheduled for retirement in 2011. The next-generation American spacecraft, named Orion, is targeted for the first manned launch in 2014 at the earliest. In between, all manned spaceflight will depend on Russian vehicles. Space transportation systems in various stages of development are reviewed in [66].

The mass driver, prototypes of which were developed and built at MIT and Princeton University, works according to the principle of the electric linear motor. Such motors also power the magnetically levitated trains built in Japan and Germany. Roughly speaking, a mass driver consists of a tube surrounded by coils that carry pulsed currents. Within the tube, “buckets” are accelerated by electromagnetic forces. These forces pull on “handles” that consist of superconducting coils that surround the buckets and carry permanent currents. The buckets are filled with material, and within short intervals they are accelerated one after another within the tube at high velocities. At the end of the acceleration distance they are slowed to a halt, and their material flies off by inertia – just like water is released from a swaying bucket. The buckets are reloaded with material and recirculated to the initial position for another acceleration run.

If the mass driver is used as a rocket engine, the ejected masses provide thrust according to the recoil principle.

Stationed on the Moon, the mass driver can serve as a catapult for lunar material to space manufacturing facilities at stable Lagrange (libration) points of the Earth–Moon system. There, according to Lagrange’s solution of the three-body problem, a small body would remain forever at equal distance from the Earth and Moon.[28] However, the presence of the distant but gravitationally powerful Sun changes Lagrange’s three-body problem into a four-body problem. Its solution shows that the stable libration points L4 and L5 change to stable regions that move in orbits of very large dimensions about L4 and L5. In each of these regions a great number of habitats could be located, circulating about their Lagrange points on a slow, 89-day cycle [69]. Each habitat could accommodate many times the workforce required for building SPS [68].

The Apollo missions to the Moon brought samples of lunar material to Earth, which show the following typical soil composition (in weight percentages): 20% silicon, 12% aluminum, 4% iron, 3% magnesium, 40% oxygen. These elements are well suited for the construction of SPS and habitats. There has been speculation that hydrogen may have accumulated around the poles of the Moon. If this is not the case, hydrogen will be the only essential element of life-supporting systems that has to be supplied from Earth.

O’Neill’s “low (profile) road” scenario for SPS construction was based on the following building blocks and estimates [67]:

1. The Space Shuttle transports a payload of about 29 t per flight. Six flights can deliver the components of a 170-t mass driver to LEO. There they are assembled

[28]The mathematician Joseph Lagrange discovered five special points in the vicinity of two orbiting masses where a third, smaller mass can orbit at a fixed distance from the larger masses. The Lagrange points mark the positions where the gravitational pull of the two large masses precisely provides the centripetal force required to rotate with them. Of the five Lagrange points, three are unstable and two are stable. The unstable Lagrange points – labeled L1, L2, and L3 – lie along the line connecting the two large masses. The stable Lagrange points – labeled L4 and L5 – form the apex of two equilateral triangles that have the large masses at their vertices.

into a heavy-duty space transporter powered by electricity from solar cell arrays. The only throwaway component of the Space Shuttle is the 35-t external tank, which is usually jettisoned shortly before LEO is reached. If one forgoes a small percentage of payload, however, the external tank can be brought into LEO and ground there into a fine powder that serves as reaction mass for the mass driver. Sixty Space Shuttle flights per year accumulate 1,700 t of payload and 2,100 t of reaction mass. The mass driver of the heavy-duty space transporter accelerates the pulverized reaction mass to 10,000 m/s and carries a payload of 1,300 t during a 200-day trip from LEO to an orbit around the Moon. Moon landing of the payload is by chemical rockets.

2. The lunar base to be built consists essentially of a mass driver, length 4,320 m, which accelerates lunar material to lunar escape velocity of 2.4 km/s. After traveling 63,000 km through space, the material is caught by a "catcher" in the Lagrange libration point L2 and transported from there by simple freighters to the first space manufacturing facilities for SPS and habitats. The annual material throughput is initially 30,000 t and later 600,000 t. The Moon Base also comprises solar power stations, service stations, waste heat radiators and housing units for initially 50 persons, and after testing and assembly of the mass driver ten persons may be sufficient to maintain routine operations. The total mass of the base is estimated to be 1,085 t, including 180 t of a 1-year food supply. To soft-land this mass on the Moon one needs the same mass of fuel (liquid oxygen and hydrogen). Furthermore, one needs installations such as the "catcher" and quarters for space workers close to the Moon. All in, about 100 Space Shuttle flights must bring 2,800 t of payload into space to initiate material transport from the surface of the Moon to some point in space at a rate of 30,000 t/year.
3. The first space manufacturing facility for chemical processing of lunar material has a mass of 150 t. A 46-MW solar cell power station, having a mass of 245 t, supplies the necessary energy. The required workforce is 150 people. Annually, 9,000 t of metal and silicon and about 7,000 t of oxygen are produced from 30,000 t of lunar raw material. The oxygen is used as breathing air for people and as liquid reaction mass for the heavy-duty space transporters, so that the Space Shuttle external tanks must no longer be pulverized but can serve as the first orbital living quarters.

   Fresh supply of 1,800 t/year should be delivered to LEO by new heavy-lift vehicles with a carrying capacity of 87 t, to be developed from the Space Shuttle. The number of personnel in space should increase by 150 persons per year, transported on 13 Space Shuttle flights. Then, the production capacity of the system would grow by 150,000 t annually. Seven to nine years after the program start, 630,000 t of raw materials and 190,000 t of finished products would be produced annually. This corresponds to the mass of two 10,000-MW SPS. After that about two SPS could be produced per year.

The cost estimates were based on numbers available in the 1970s for very complex and not-so-complex space systems: research and development \$28,000–\$62,000/kg, construction cost \$1,100/kg, transportation cost \$230–\$690/kg, interest

10%. Assuming an SPS value of \$500 per kW power delivery at a bus bar on Earth, the financial break-even point could be reached within 10 years of the start after having invested $\$_{1978}$50 billion to $\$_{1978}$60 billion. The Apollo Moon Program would have cost that much in the mid-1970s. Although the cost estimate was too optimistic in view of the cost accumulated by the Space Shuttle program, O'Neill's "Low (Profile) Road to Space Manufacturing" indicates a way of building SPS mostly from extraterrestrial resources that should not be forgotten.

O'Neill died from leukemia on April 27, 1992, at the age of 65. During the Seventh Princeton University Conference on Space Manufacturing Facilities in 1985, the year his leukemia was diagnosed, he told me: "I have mortgaged all my property up to the last sock in order to found and operate Geostar Corporation." On the basis of a patent for a satellite position determination system, granted to O'Neill in 1982, Geostar was supposed to generate the funds for continuing research into space manufacturing. After the first oil price shock in 1973–1975 public funding for such research was good. But when oil prices plummeted to nearly pre-1973 levels between 1981 and 1985, public funds dried up. One year before O'Neill's death, Geostar went bankrupt. The Space Studies Institute (http://ssi.org/), formerly at Princeton (NJ, USA), now at Mojave (CA, USA), preserves O'Neill's legacy.

When energy prices increase and concerns about emissions from fossil fuel combustion mount, new legislative initiatives may remember the "House Concurrent Resolution 451," presented to the 95th Congress of the United States of America by Representative Olin Teague on December 15, 1977, and referred to the Committee on Science and Technology. It states [67]:

"*Whereas* historically it is an inherent genius of the American people that we vigorously reach out to explore, to fulfill and enhance the resources of new and challenging frontiers, for the benefit of all humanity; and
Whereas the magnificent achievements of our explorations into space in the past twenty years have proved decisively that this tiny Earth is not humanity's prison, is not a closed and dwindling resource, but is in fact only part of a vast expanding system rich in extraterrestrial opportunities as yet far beyond our comprehension, a "high frontier" which irresistibly beckons and challenges the American genius; and
Whereas our ventures into space, though daring, have not been rash, but have in fact succeeded only because of rigorous, disciplined, careful analysis, planning, training and skilled performance, thus establishing standards and precedents which must continue to guide all further national policy decisions and efforts in space; and
Whereas … many Americans seem for the moment beset and confused by complex problems, discouraged by alleged "limits to growth" and by careless waste of the Earth's resources …; and
Whereas the "High Frontier" of Space does provide valid opportunities whereby we can conserve and enhance humanity's existence on Earth, including but not limited to such social and economic benefits as greater employment, a cleaner environment, new energy sources, new knowledge and understanding …: Now, therefore be it

Resolved by the House of Representatives (the Senate concurring), That the Congress hereby finds and declares the following national policy:

(1) It is vital to the well-being of the American people, and all the people on this Earth, that every feasible means now shall be mobilized to explore and assess the resources of the "high frontier" of outer space, to better understand and to make practical, beneficial uses of these resources.
(2) As immediate priorities, research efforts shall be intensified to reveal and to better understand the solar system and the universe beyond it, to develop a practical, efficient transportation system in space ...
(3) As long range, high priority national goals, it is anticipated that by the year 2000 these explorations will have opened the resources and environment of extraterrestrial space to an as yet incalculable range of other positive uses, including but not limited to, international cooperation for the maintenance of peace, the discovery and development of new sources of energy and materials, industrial processing and manufacturing ... and, conceivably, the establishment of self-sustaining communities in space.

The Congress hereby encourages and instructs all pertinent legislative committees and executive agencies to determine how they may most effectively act ... to achieve these urgent national goals.

To assist in these efforts the Office for Technology Assessment specifically is requested to organize and manage a thorough study and analysis to determine the feasibility, potential consequences, advantages and disadvantages of developing as a national goal for the year 2000 the first manned structures in space for the conversion of solar energy and other extraterrestrial resources to the peaceable and practical use of human beings everywhere."

The Advanced Concepts Team of the European Space Agency[29] has been considering solar power from satellites and terrestrial sun farms. In 2004 it compared space concepts with terrestrial solutions based on equally advanced technology and equal economic conditions for the time frame 2020–2030 in terms of energy payback times, final euros per kilowatt-hour generation cost, adaptability to different energy scenarios, reliability, and risk [70]. The conclusions were: "While terrestrial solar power plants will already play an increasing part in European electricity production in the next 20 years, solar power satellites will technically and economically reach their maturation phase only at the end of the considered time frame. The competitiveness of the space option increases with increasing total plant sizes. Under the given assumptions, space options are not competitive with terrestrial plants for relatively small solar power plants (depending on the type from 0.5 to 50 GW_{el}). Earth-to-orbit transportation is the single most important factor requiring a decrease of more than one order of magnitude compared to current launch costs. Depending on the plant size, launch costs between 155 and 1615 euro per kg_{LEO} (kilogram into Low Earth Orbit) for peak load and around 600–700 euro per kg_{LEO}

[29] http://www.esa.int/gsp/ACT/publications/index.htm .

for base-load supply scenarios are necessary to be competitive with terrestrial solar power plants. … Both, space and large terrestrial solar power plants have very attractive, low energy payback times. Both laser and microwave power transmission concepts show energy payback times of only a few months. Almost all space and terrestrial concepts produce within less than one year more energy than was needed to produce and operate them, based on detailed material flow analysis."

In 2007, the National Space Security Office authored the study *Space-Based Solar Power As an Opportunity for Strategic Security* [71]. It states in its Executive Summary: "The magnitude of the looming energy and environmental problems is significant enough to warrant considerations of all options, including revisiting a concept called Space Based Solar Power (SBSP) first invented in the USA almost 40 years ago." Its recommendations conclude with: "The study group recommends that the US Government should become an early demonstrator/adopter/customer of SBSP and incentivice its development."

Appendix 1: Basic Forms of Energy

The many manifestations of energy occur in a great variety of systems. Physical systems consist of components, constraints, and boundaries. Components are "particles" (with and without mass) in any number, and the forces that act on them. Constraints restrict the motions and interactions of the components. Boundaries – material or immaterial ones – separate systems from one another.

System Energies

System energies are *properties* of systems. They differ from energy forms that are *exchanged* between systems. It is important to discriminate between these two forms of energy in energy conversion processes:

1. *Kinetic energy* is the energy of motion. Its simplest form shows in a system that consists of configuration space spanned by the three Cartesian coordinates x, y, z and a body of mass m, whose center moves with velocity $\mathbf{v}$ relative to an observer at rest. If, as we will always assume from here on, the velocity of the mass is much less than the speed of light, i.e. ,$|\mathbf{v}| \ll c$, the kinetic energy of that body measured by the observer is

$$E_{\text{kin}} = \frac{1}{2}m\mathbf{v}^2 = \frac{\mathbf{p}^2}{2m}, \tag{2.18}$$

where $\mathbf{p} = m\mathbf{v}$ is the momentum of the body.[30]

[30]More generally $E_{\text{kin}} = (m - m_0)c^2 \approx (1/2)m_0\mathbf{v}^2 + (3\mathbf{v}^2/8c^2)m_0\mathbf{v}^2 + \dots$. This becomes important when $|\mathbf{v}|$ approaches c, so $m = m_0/(1 - \mathbf{v}^2/c^2)^{1/2}$ differs substantially from m_0.

Kinetic energy creates wealth in hammers, sickles, windmills, steam turbines, gas turbines, and other tools and machines. In general, each tiny mass element Δm of these bodies, in its position $\mathbf{r} \equiv (x, y, z)$, has its own velocity $\mathbf{v}(\mathbf{r}, t)$, which changes with time t if forces act on the bodies, and its kinetic energy is given by (2.18), with Δm in place of m. The total kinetic energy of each body is the sum of the kinetic energies of all its elements. Kinetic energy also works destructively in swords, arrows, bullets, shell fragments, tsunamis, and hurricanes. In water and air the mass elements are molecules.

2. *Potential energy in a gravitational field.* Consider a body of mass m, whose center of mass has been elevated against the pull of Earth's gravity from the ground to a level at height h above the ground. It has acquired the potential energy

$$E_{\text{pot}} = mgh \tag{2.19}$$

relative to the ground, where $g = 9.81 \ \text{m/s}^2$ is the acceleration in the gravitational field of Earth.

Water dams accumulate the potential energy of water provided by the Sun. Conversion of this potential energy into kinetic energy, when the water rushes through the turbines of water power stations, provided nearly 20% of the 16,379 TWh of electricity generated globally in 2006.

A more general case of gravitational potential energy is realized in a system that consists of two masses m_1 and m_2 (e.g., a sun and its only planet) whose centers are located at positions $\mathbf{r_1}$ and $\mathbf{r_2}$. The two masses attract each other gravitationally, and the potential energy of mass m_1 in the gravitational field of mass m_2, and vice versa, is given by Newton's gravitational law

$$E_{\text{grav}} = -\gamma \frac{m_1 m_2}{|\mathbf{r_1} - \mathbf{r_2}|}; \tag{2.20}$$

$\gamma = 6.672 \times 10^{-11}$ N m^2/kg^{-2} is the gravitational constant. The negative sign takes into account that apples fall from trees, like the famous one of physics legend that fell upon Isaac Newton's head and put the gravitational law into it: $|\mathbf{r_1} - \mathbf{r_2}|$ is the distance between the center of mass of the apple on the tree and the center of Earth. When the apple broke off from the tree and this distance decreased by a few meters, E_{grav} became more negative. The lost potential energy became kinetic energy transferred from the apple to Newton's head, stimulating the idea that led to Newtonian classical mechanics.

3. *Coulomb energy.* Let a system consist of two pointlike charges q_1 and q_2 that occupy positions $\mathbf{r_1}$ and $\mathbf{r_2}$. The potential energy of charge q_1 in the electric field of charge q_2 (and vice versa) bears the name of Coulomb and has the magnitude

$$E_{\text{coul}} = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{|\mathbf{r_1} - \mathbf{r_2}|}; \tag{2.21}$$

$\varepsilon_0 = 8.8542 \times 10^{-12}$ A s/V m is the dielectric constant of vacuum.

Coulomb energy (2.21) and gravitational energy (2.20) look alike: charges correspond to masses and the *absolute* magnitude of energy increases as the distance $|\mathbf{r_1} - \mathbf{r_2}|$ between the interacting partners decreases. But although there is always attraction between masses, which is taken care of by the minus sign in (2.20), only charges of opposite sign attract each other. Charges of the same sign repel each other; their potential energy is smaller the farther they are apart. Furthermore, the smallest mass elements in all systems, where nuclear reactions do not matter, are atoms, which differ in size and mass. The smallest charge elements, however, the positively charged protons and the negatively charged electrons, have exactly the *same* absolute magnitude of charge. This is the elementary charge $e = 1.602 \times 10^{-19}$ A s. Although the mass of the proton, $m_p = 1.672 \times 10^{-27}$ kg, exceeds the mass of an electron, $m_e = 9.108 \times 10^{-31}$ kg, by more than a factor of 1,000, it is justified in most cases to treat both as pointlike charges.

The similarity of (2.21) and (2.20) is one justification of Rutherford's planetary model of the atom: nearly all the mass of the atom is concentrated in the positively charged core of protons and neutrons, whereas the light electrons encircle this core in orbits similar to the planetary orbits around the Sun. However, this model contradicts the laws of classical physics, according to which an orbiting electron would emit electromagnetic radiation; this energy loss would more and more reduce the electron's distance to the nucleus (the right-hand side of (2.21) is negative for q_1 positive and q_2 negative) so the orbit would not be stable. Rather, the electron would spiral down into the nuclear core. But quantum mechanics has replaced classical physics in the description of atoms. Quantum mechanically there are (only) probabilities of finding an electron with stable, quantized energies at certain distances from the nucleus without any radiative energy losses being involved.

In thunderstorms, clouds and earth accumulate opposite charges, building up huge amounts of Coulomb energy. In a lightning flash, about 100 kWh is liberated by a principal discharge. This energy is the same as the amount of energy required to lift a mass of 4.1 t from sea level to the peak of Mount Everest at 8,848 m. Coulomb energy is the interaction energy in all many-particle systems consisting of electrons and stable nuclei. These systems are discussed below in the context of chemical energy.

4. *Energy of electric and magnetic fields*. The energy density of electric and magnetic fields $\mathbf{E}$ and $\mathbf{H}$ in a vacuum is

$$\eta = \frac{1}{2}\varepsilon_0 \mathbf{E}^2 + \frac{1}{2}\mu_0 \mathbf{H}^2, \tag{2.22}$$

where $\mu_0 = 4\pi \times 10^{-7}$ V s/A m is the permeability of a vacuum. Thus, a system that contains these fields within a certain volume V of (practically empty) space has the electromagnetic energy that is the integral of the energy density η over the volume:

$$E_{\text{elmag}} = \int_V \eta \mathrm{d}V. \tag{2.23}$$

Information in telecommunications is imprinted on propagating electromagnetic waves with oscillating **E** and **H** vectors. These waves are emitted by oscillating charges in the antennas of mobile phones, radio stations, and TV stations. Lasers that emit rays of high energy density η are used as cutting and welding tools in surgery and laser-assisted machining of materials.

5. *Photon energy*. The energy quanta of an electromagnetic wave, whose electric and magnetic field vectors **E** and **H** oscillate with angular velocity ω, are photons of energy

$$E_{\text{photon}} = \hbar\omega. \tag{2.24}$$

Here $\hbar = 1.0546 \times 10^{-34}$ W s^2 is Planck's constant divided by 2π.

Photons carry the Sun's radiation to Earth.

6. *Radiation energy inside a cavity with wall temperature T*. A cavity of volume V, whose walls are maintained at the absolute temperature T, is a system we encounter in blast furnaces, combustion chambers of power stations, and rooms. The electromagnetic radiation that exists in thermal equilibrium as an assembly of photons inside such a cavity has an energy density $u_0(T)$ that increases with the fourth power of T:

$$u_0(T) = \frac{\pi^2}{15}\frac{(k_B T)^4}{(c\hbar)^3}, \tag{2.25}$$

where $k_B = 1.3807 \times 10^{-23}$ W s/K is Boltzmann's constant. Thus, the radiation energy contained in the volume V is the integral of the energy density $u_0(T)$ over this volume,

$$E_{\text{rad}} = \int_V u_0(T)\mathrm{d}V, \tag{2.26}$$

and is proportional to T^4.

7. *Internal energy (chemical energy) of an interacting many-particle system*. Solids, fluids, and gases are formed by atomic nuclei and electrons that interact with each other via the Coulomb energy of (2.21). Let us consider a system of many particles that are enclosed in a box with rigid, insulating walls, which form the system boundaries. The particles are L nuclei and N electrons. The nuclei at positions $\mathbf{R}_i$ have masses M_i, momenta $\mathbf{P}_i$, and positive charges $Z_i e$. The electrons at positions $\mathbf{r}_k$ have masses m, momenta $\mathbf{p}_k$, and charges $-e$. The total energy of the system, called a Hamiltonian, is the sum of all kinetic and Coulomb energies:

$$\mathscr{H} = \sum_{i=1}^{L}\frac{\mathbf{P}_i^2}{2M_i} + \frac{1}{2}\sum_{i\neq j}^{L}\frac{1}{4\pi\varepsilon_0}\frac{e^2 Z_i Z_j}{|\mathbf{R}_i - \mathbf{R}_j|} + \sum_{k=1}^{N}\frac{\mathbf{p}_k^2}{2m} + \frac{1}{2}\sum_{k\neq l}^{N}\frac{1}{4\pi\varepsilon_0}\frac{e^2}{|\mathbf{r}_k - \mathbf{r}_l|}$$
$$- \sum_{i,k}^{L,N}\frac{1}{4\pi\varepsilon_0}\frac{e^2 Z_i}{|\mathbf{R}_i - \mathbf{r}_k|}. \tag{2.27}$$

An experimenter has prepared the system in such a way that its total energy is in a narrow energy interval between E and $E + \delta E$. The system is completely isolated and in equilibrium. For a macroscopic system, even a very small energy interval δE contains a huge number of many-particle states. These states are characterized either classically by all particle positions and momenta compatible with the boundaries, or quantum mechanically by as many quantum numbers as independent coordinates are needed for the description of the system. (The number of these coordinates is called the "number of degrees of freedom.") In order to count the states they are labeled by, say, r. For $1\,\mathrm{cm}^3$ of any metal, or $1\,\mathrm{m}^3$ of air, the label r runs from 1 to numbers so large that infinity is a good approximation. The corresponding many-body states are symbolized by $|\Phi_r>$. Let $\Omega(E)$ denote the number of many-particle states $|\Phi_r>$ whose energies[31] E_r lie between E and $E + \delta E$. The fundamental postulate of statistical physics says that the system occupies with equal probability any one of these $\Omega(E)$ states; see also Chap. 3. Accordingly, it can be found with equal probability in any one of the $\Omega(E)$ states $|\Phi_r>$. Thus, the *internal energy* U of the system, defined as the average of all energies E_r between $E_r = E$ and $E_r = E + \delta E$, is the sum of all energies in this range divided by the number of states in this range:

$$U = \frac{1}{\Omega(E)} \sum_{|\Phi_r>;E}^{E+\delta E} E_r. \tag{2.28}$$

The minimum internal energy is that of the ground state. A system would occupy its ground state at the zero point of absolute temperature, i.e., at $T = 0$ K. Internal energy is also called *chemical energy*. Computation of the internal energy of an interacting many-particle system by field-theoretical methods [3, 4] is a frontier of modern physics.

Industrial production has been powered for 200 years by the chemical energy of fossil fuels. Solar photons may be converted into and stored by the chemical energy of novel fuels such as hydrogen.

8. *Energy stored in capacitors and current rings*. A capacitor with capacitance C, carrying charges $+q$ and $-q$ on its two conductors, stores the electrostatic energy

$$E_{\mathrm{elst}} = \frac{q^2}{2C}. \tag{2.29}$$

A current-carrying circuit stores the magnetic energy

$$E_{\mathrm{mag}} = \frac{1}{2} L I^2, \tag{2.30}$$

[31] Quantum mechanics computes E_r as the expectation value of the Hamiltonian (2.27) with $|\Phi_r>$: $E_r =< \Phi_r|\mathscr{H}|\Phi_r>$.

where I is the current in and L is the self-inductance of the circuit. If the circuit is superconducting, the current circulates permanently without any energy dissipation. Electrostatic and magnetic storage of electric energy may complement the presently dominating chemical storage in batteries. Low-cost, efficient energy storage is decisive for utilizing the energy of fluctuating wind and sunshine fully.

Work and Heat

Work and heat are the energy forms people are most familiar with, because they are directly accessible to our senses. They originate in energy conversion processes from changes of system energies and are conceptually different from them: They are energy forms that *transgress* system boundaries.

Work

If a system interacts with its environment, mechanical work W is performed by a force $\mathbf{F}$ on a moving system boundary. Such a boundary can be the surface of a plow or of a piston, or the handle of a weight to be lifted, or any other contact between a system and the force that acts upon the system. An infinitesimal displacement $\mathrm{d}\mathbf{r}$ of the boundary requires an infinitesimal amount δW of mechanical work performed by the force *on* the system. This work is equal to the scalar product of the force vector $\mathbf{F}$ with the path element $\mathrm{d}\mathbf{r}$:

$$\delta W = \mathbf{F}\,\mathrm{d}\mathbf{r}. \tag{2.31}$$

The total work performed *on* the system *by* the environment during a finite displacement of the system boundary from space point 1 to space point 2 is given by the integral

$$W_{12} = \int_1^2 \mathbf{F}\,\mathrm{d}\mathbf{r}. \tag{2.32}$$

If W_{12} is positive (negative), the system receives (transfers) energy from (to) the environment.

Two special cases of *mechanical* work are external mechanical work and work of volume change. *External* mechanical work W^{MEx} is done *on* a system, if the velocities $\mathbf{v}$ of the elements $\mathrm{d}m$ of total system mass m are changed, and if the position z of the center of mass is displaced in a gravitational field that produces the acceleration $\mathbf{g}$ in negative z direction:

$$W_{12}^{\mathrm{MEx}} = \frac{1}{2}\left(\int \mathbf{v}^2\,\mathrm{d}m\right)_2 - \frac{1}{2}\left(\int \mathbf{v}^2\,\mathrm{d}m\right)_1 + mg\,(z_2 - z_1)\,. \tag{2.33}$$

The integrals represent the difference of kinetic energy in the system states 2 and 1 after and before W_{12}^{MEx} has been performed on the system, and the remainder is the change of potential energy of the system. If rotatory motions with different velocities of the mass elements are involved, states 2 and 1 are characterized not only by changed positions of the system boundaries but also by angular changes. Mechanical work of *volume* change W^{MV} is done *on* a system that rests as a whole if forces from the environment act perpendicularly to the system boundaries and change the system volume V. Consider a fluid or a gas enclosed in a cylinder with a movable piston. The area A of the piston is the system boundary. At rest the piston is kept in equilibrium by an external force **F** that balances the force from the pressure p of the fluid or gas:

$$\mathbf{F} = -p\mathbf{A}. \tag{2.34}$$

The direction of **F** is antiparallel to the area vector **A**, which is directed outwardly. A displacement of the piston by the distance d**r** changes the volume of the fluid or gas by $\mathrm{d}V = \mathbf{A}\,\mathrm{d}\mathbf{r}$. If the piston movement displaces the external force **F** so slowly that it remains in equilibrium with the force $-p\mathbf{A}$, the work performed in this *quasistatic* process *on* the system is according to (2.31) and (2.34)

$$\delta W^{\mathrm{MV}} = \mathbf{F}\,\mathrm{d}\mathbf{r} = -p\,\mathrm{d}V. \tag{2.35}$$

During compression $\mathrm{d}V < 0$ and $\delta W^{\mathrm{MV}} > 0$; the system receives energy *from* the environment. During expansion $\mathrm{d}V > 0$ and $\delta W^{\mathrm{MV}} < 0$; the system supplies energy *to* the environment.

During piston motion, pressure p and volume V change with time t. The computation of $p(t)$ and $V(t)$ is a difficult problem in fluid dynamics, in general. However, as long as the piston velocity is small compared with the velocity of sound in the gas or fluid, the quasistatic approximation of assuming a unique dependence $p = p(T, V)$ of pressure p on volume V and temperature T gives good results. Then (2.35) can be integrated between the initial position 1 and the final position 2 of the piston and one obtains the total work of volume change performed *on* the system by the environment as

$$W_{12}^{\mathrm{MV}} = -\int_1^2 p\,\mathrm{d}V. \tag{2.36}$$

Electric work W^{El} is performed, if a system is connected to a voltage source, and an electric potential difference $\tilde{V}$ drives a current I through the system. The electric work done *on* the system by the voltage source between the times t_1 and t_2 is

$$W_{12}^{\mathrm{El}} = \int_{t_1}^{t_2} I \times \tilde{V}\,\mathrm{d}t. \tag{2.37}$$

In summary, if external parameters of a many-particle system do not remain fixed, but change, while the system is thermally isolated from its environment,

work W_{12} is performed *on* the system. This work changes the system's internal energy by

$$\Delta_W U \equiv U_2 - U_1 = W_{12}. \tag{2.38}$$

If $W_{12} > 0$, the system receives energy from the environment. If $W_{12} < 0$, the system transfers energy *to* the environment.

Whereas (2.28) says how to calculate internal energy theoretically, (2.38) says how to measure internal energy differences by the measurement of W_{12}.

Heat

One observes that there are processes in which (2.38) does not correctly describe the change of internal energy of a given system. Such processes occur if the system is in thermal contact with its environment. Then, another form of energy (also) crosses the system boundaries. This energy form is called *heat*. Quantitatively, in an arbitrary process that changes external parameters while there is *no* thermal isolation, the total change of the system's internal energy is

$$\Delta U = U_2 - U_1 \equiv W_{12} - Q_{12}. \tag{2.39}$$

The quantity Q_{12} thus introduced is a measure of the internal energy change *not* due to the change of external parameters. Equation (2.39) is the *definition* of the heat Q_{12} given off *by* the system *to* the environment in an arbitrary process that carries the system from state 1 to state 2. Heat, the disorderly motion of particles, is transferred by heat conduction in solids and liquids, convection in gases, and randomly oscillating electromagnetic fields. Active cooling is often required to avoid system destruction by overheating.

Heating and cooling is important for computers. Transistors in computers process digital information by blocking (0) or letting pass (1) electric currents. They are sketched in Sect. 2.3.2. The voltage that drives the current performs electric work, given by (2.37). This work eventually ends up in heat, $W_{12} = Q_{12}$ in (2.39), because the internal energy of a transistor is the same before switching on and after switching off the computer, supposing that all electrically produced Joule heat can be given off to the environment by thermal conduction.[32]

[32]Heat production is inconvenient for further evolution of computers, which has been characterized during the last four decades by a doubling of the density of transistors on a microchip every 18 months. If this trend and current trends of power consumption continue, the computer industry could possibly face the so-called Problem 2020, when the temperature of a miniaturized computer would be equal to the Sun's temperature, because the Joule heat could no longer escape sufficiently rapidly out of the densely packed compound of transistors.

Work and heat are energy forms that *cross* system boundaries. Infinitesimal quantities of them are *not* total differentials and are written as δW and δQ. Internal energy U, on the other hand, is a system *property*. It is described by a *state* function, which depends only on the system variables in the actual state and not on the path by which the system has arrived at this state. Its infinitesimal change is the total differential $\mathrm{d}U$.

Enthalpy and Exergy

Enthalpy

Consider two systems of different atoms and molecules that are initially isolated from each other. Their Hamiltonians are $\mathscr{H}_1'$ and $\mathscr{H}_1''$. Their corresponding internal energies, which are measured at constant volumes, are U_1' and U_1'', and the total initial internal energy is $U_1 = U_1' + U_1''$. Then the systems are brought in contact and interact with each other. During chemical reactions the electrons and nuclei are rearranged. When the total system has reached a new equilibrium, its internal energy is U_2.

Most chemical reactions occur at constant pressure p, not constant volume. If the total volume of the two isolated systems is initially $V_1 = V_1' + V_1''$ and the total final volume after the reaction is V_2, work $p(V_2 - V_1)$ is exchanged between the total system and the environment. This environment is the atmosphere in many cases.

The difference $U_2 - U_1$ between the final and the initial internal energies is then

$$U_2 - U_1 = -p(V_2 - V_1) - Q_{12}. \tag{2.40}$$

The chemical reaction is said to be exothermal (endothermal) if $Q_{12} > 0$ ($Q_{12} < 0$).

If one is only interested in the heat balance of chemical reactions, it is convenient to introduce a new state function, called *enthalpy*. Enthalpy H is defined as

$$H \equiv U + pV. \tag{2.41}$$

With that (2.40) can be written as

$$H_1 - H_2 = Q_{12}. \tag{2.42}$$

If both the initial and the final states of a chemical reaction are solids or fluids, the difference between enthalpy H and internal energy U is small. If, however, gaseous states are involved, as happens during the combustion of fossil fuels, one must calculate the produced heat from (2.42).

Exergy

Energy quantity, measured in enthalpy units such as joules (or tons of oil/coal equivalents, or kilowatt-hours, or Board of Trade Units) is not sufficient to characterize the usefulness of an energy carrier, in general. Energy *quality* is important too. According to Karlsson [73] and van Gool [74], energy quality is defined as

$$\text{Quality} = \text{exergy/enthalpy}.$$

Exergy is the share of an energy quantity that can be completely converted into physical work. It is complemented by useless anergy in the energy conservation equation (2.2).

> In all real-life energy conversion processes, useless anergy grows at the expense of useful exergy.

Examples of exergy are:

1. The kinetic energy of a mass m with velocity $\mathbf{v}$ is 100% exergy. The same is true for the potential energy of this mass in a gravitational field.
2. Electric energy is 100% exergy.
3. The chemical energy stored in coal, oil, and gas is practically 100% exergy. The same is true for the energy obtained from mass conversion according to $E = mc^2$. This is because very high temperatures can be obtained, in principle, from fossil-fuel combustion and mass-to-energy conversion. Hence, the Carnot efficiency (2.17) and the quality of heat, as given in example 5, can be very close to 1.
4. Solar radiation is practically 100% exergy. For electromagnetic radiation Karlsson [73] has shown that the quality of a quasi-monochromatic beam of incoherent radiation in an angular frequency range between ω and $\omega + \mathrm{d}\omega$, falling perpendicularly onto the surface of a black body at temperature T_0, is

$$\begin{aligned}\text{Exergy/enthalpy} &= 1 - T_0/T + [\exp(\hbar\omega/k_B T) - 1] \\ &\quad \times (k_B T_0/\hbar\omega) \ln \frac{[1 - \exp(-\hbar\omega/k_B T)]}{[1 - \exp(-\hbar\omega/k_B T_0)]}. \end{aligned} \tag{2.43}$$

   Here,

$$T = \hbar\omega / \{k_B \ln[(2\hbar\omega^3/c^2 P_E) + 1]\} \tag{2.44}$$

   is the equivalent temperature of a black body that emits power $P_E(\omega)\mathrm{d}\omega$ per unit area in the frequency range between ω and $\omega + \mathrm{d}\omega$. If T is equal to the effective solar surface temperature of 5,777 K, and T_0 is a temperature of the

order of 288 K, the average surface temperature of Earth, the quality of the corresponding black-body radiation is close to 1 [73].

5. Heat of quantity Q at temperature T, in an environment of temperature T_0, contains the exergy $E_X = Q(1-T_0/T)$. Thus, its quality is given by the Carnot efficiency $1 - T_0/T$, defined in (2.17).
6. A many-particle system of internal energy U, entropy S, and volume V, which is out of equilibrium with its environment of temperature T_0 and pressure p_0, and which can exchange heat and work – but not matter – with the environment, contains the exergy [5, 72]

$$E_X = (U - U_0) + p_0(V - V_0) - T_0(S - S_0). \tag{2.45}$$

Here, U_0, V_0, and S_0 are internal energy, volume, and entropy when the system has come to equilibrium with its environment. The internal energy U is given by (2.28). Entropy S, the physical measure of disorder in the system, is defined statistically as

$$S = k_B \ln \Omega. \tag{2.46}$$

Section 3.4.1 goes into this in more detail. Ω, the number of many-particle states accessible to the system within a given energy range, has already been used in (2.28), which defines internal energy U.

7. A thermodynamic system of volume V at pressure p, with a stationary current of mass m and kinetic energy $m\mathbf{v}^2/2$ entering it at one place and leaving it at another place, having the potential energy mgz at height z above a reference point in the gravitational field of acceleration g, contains the exergy [5, 72]

$$E_X = (U + pV - U_0 - p_0 V_0) - T_0(S - S_0) + m\mathbf{v}^2/2 + mgz.$$

8. Consider a combustion process that produces a many-particle system of internal energy U, entropy S, and volume V. The system is out of equilibrium with its environment of temperature T_0 and pressure p_0. It can exchange heat, work, and matter with the environment. The concentration of the combustion products in the combustion chamber is higher than that in the environment. In principle, work can be obtained from their diffusion into the environment. To compute this work, which contributes to exergy, one pretends that immediately after combustion the system components are mixed and already in thermal and mechanical equilibrium with the environment, but that they have not yet left the combustion chamber. Then they leave the combustion chamber and diffuse. Thus, if the system consists of N different sorts i of particles, with n_i being the number of particles of component i, and if μ_{i0} and μ_{id} are the chemical potentials of component i in thermal and mechanical equilibrium before and after diffusion, respectively, then the exergy content of the system is [72]

$$E_X = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + \sum_{i=1}^{N} n_i(\mu_{i0} - \mu_{id}); \tag{2.47}$$

here the kinetic and potential energies of the components have been disregarded.

Thermodynamic Potentials

What is the difference between exergy and the "free energies" represented by the thermodynamic potentials Helmholtz free energy and Gibbs free energy?

Thermodynamic potentials are used in equilibrium thermodynamics when *quasistatic* processes are described. Quasistatic processes occur so slowly that the relaxation mechanisms in the many-particle system maintain equilibrium practically always. Nevertheless, equilibrium thermodynamics can also describe results of nonequilibrium processes if one is only interested in changes of thermodynamic potentials. These are state functions of equilibrium systems, and state functions (like internal energy or enthalpy) are independent of the process that has brought the system into its actual state.[33]

There are four thermodynamic potentials that describe many-particle systems according to their interaction with the environment or reservoirs: internal energy U, enthalpy H, Helmholtz free energy F, and Gibbs free energy G. They are related to each other by *Legendre transformations*.

Isolated System: $U(S, V)$

To work out the basic relations, we first consider a homogeneous system that is isolated from its environment; its particle number does not change. Its internal energy has been defined in (2.28). With (2.46), which defines entropy S, internal energy U becomes

$$U = \exp(-S/k_\mathrm{B}) \sum_{|\Phi_r>;E}^{E+\delta E} E_r. \tag{2.48}$$

Entropy is determined by preparing the system in the energy range between E and $E+\delta E$ with the corresponding number of accessible states $\Omega(E)$. Internal energy U also depends on external parameters. These parameters fix the boundary conditions, which determine the energy eigenvalues E_r of the many-particle states $|\Phi_r>$ of a given Hamiltonian $\mathscr{H}$. Enclosing the system within a volume V fixes the boundary conditions. Thus, entropy S and volume V can be chosen freely by an experimenter who prepares the system in a state of his liking. They are the independent variables of the state function

$$U = U(S, V). \tag{2.49}$$

[33]For instance, if one puts a pot of cold water on a hot plate, the heating process is not quasistatic, but the heat given off by the hot plate to the water can be simply calculated as the difference between the enthalpies of the water in the hot and in the cold state.

We recall that state functions are uniquely determined by their independent variables. Thus, their infinitesimal changes are total differentials, and their second-order mixed derivatives are equal.

The statistical definition (2.46) of entropy implies the statistical definition of absolute temperature T:

$$\frac{1}{T} = \left(\frac{\partial S}{\partial U}\right)_V . \tag{2.50}$$

This is shown by the derivation of (3.14) in Chap. 3. With that the total differential

$$\mathrm{d}U = \left(\frac{\partial U}{\partial S}\right)_V \mathrm{d}S + \left(\frac{\partial U}{\partial V}\right)_S \mathrm{d}V \tag{2.51}$$

becomes

$$\mathrm{d}U = T\mathrm{d}S + \left(\frac{\partial U}{\partial V}\right)_S \mathrm{d}V. \tag{2.52}$$

We write (2.40) for quasistatic transitions between two infinitesimally close states 1 and 2. Then $U_2 - U_1 \equiv \mathrm{d}U$, $V_2 - V_1 \equiv \mathrm{d}V$, and $-Q_{12} \equiv \delta Q$. By convention and definition δQ is the infinitesimal amount of heat the system *absorbs* in a quasistatic process. With that (2.40) changes into

$$\mathrm{d}U = \delta Q - p\mathrm{d}V. \tag{2.53}$$

In equilibrium thermodynamics, this equation is called the first law of thermodynamics.

Comparison of (2.52) and (2.53) yields

$$\mathrm{d}S = \frac{\delta Q}{T} \tag{2.54}$$

and

$$p = -\left(\frac{\partial U}{\partial V}\right)_S . \tag{2.55}$$

In equilibrium thermodynamics, (2.54) is the phenomenological definition of entropy, whereby absolute temperature T plays the role of an integrating factor, which produces the total differential $\mathrm{d}S$ from the infinitesimal δQ. The standard form of the first law of thermodynamics for quasistatic mechanical work of volume change and heat exchange with the environment is obtained by combining (2.54) and (2.53):

$$\mathrm{d}U = T\mathrm{d}S - p\mathrm{d}V. \tag{2.56}$$

According to its derivation, it is only appropriate for changes that can be approximated by infinitely slow, reversible processes.

Since the second-order mixed derivatives of $U(S, V)$ must be equal, i.e.,

$$\frac{\partial^2 U}{\partial S \partial V} = \frac{\partial^2 U}{\partial V \partial S}, \tag{2.57}$$

and since $\left(\frac{\partial U}{\partial V}\right)_S = -p$, and $\left(\frac{\partial U}{\partial S}\right)_V = T$, we obtain the first of the so-called Maxwell relations:

$$-\left(\frac{\partial p}{\partial S}\right)_V = \left(\frac{\partial T}{\partial V}\right)_S. \tag{2.58}$$

Subsequently, we consider systems in contact with a reservoir. By definition, a reservoir is so large that its temperature, pressure, and chemical composition remain practically unchanged during interactions with the systems under consideration. This is the case if the number of degrees of freedom in the reservoir is very much larger than that in the systems. Of course, the natural environment satisfies the reservoir conditions.

System in Contact with a Reservoir at Constant Pressure: $H(S, p)$

We have seen above that enthalpy H is the appropriate state function of a system in contact with a reservoir that maintains a constant pressure p on the system. Thus, pressure p replaces volume V as the independent variable to be chosen by the experimenter. Formally, H is obtained from U by the Legendre transformation

$$H = U + pV. \tag{2.59}$$

Then the total differential

$$\mathrm{d}H = \mathrm{d}U + p\mathrm{d}V + V\mathrm{d}p = T\mathrm{d}S + V\mathrm{d}p \tag{2.60}$$

has S and p as the independent variables of H, where (2.56) has been used. Reasoning like that which leads to the first Maxwell relation (2.58) yields the second Maxwell relation:

$$\left(\frac{\partial T}{\partial p}\right)_S = \left(\frac{\partial V}{\partial S}\right)_p. \tag{2.61}$$

System in Contact with a Reservoir at Constant Temperature: $F(T, V)$

If a system with fixed volume V is brought into thermal contact and equilibrium with a reservoir at constant temperature T, the independent variables that determine the system properties are T and V. The Legendre transformation to the state function Helmholtz free energy F is

$$F = U - TS. \tag{2.62}$$

The total differential is

$$dF = dU - TdS - SdT = -SdT - pdV, \tag{2.63}$$

where, again, (2.56) has been used. Thus, $F = F(T, V)$, and the third Maxwell relation results from the equality of the second-order mixed derivatives of $F(T, V)$ as

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial p}{\partial T}\right)_V. \tag{2.64}$$

In equilibrium, F is minimum.

System in Contact with a Reservoir at Constant Temperature and Pressure: *G*(*T*, *p*)

If a system is brought into thermal contact and equilibrium with a reservoir at temperature T, and if its volume may change so that the system assumes the same pressure p as the reservoir, the independent variables that determine the system properties are T and p. The Legendre transformation to the state function Gibbs free energy G is

$$G \equiv U - TS + pV. \tag{2.65}$$

The total differential of G becomes, in combination with (2.56),

$$dG = dU - TdS - SdT + pdV + Vdp = -SdT + Vdp. \tag{2.66}$$

The fourth Maxwell relation results from the equality of the second-order mixed derivatives of $G(T, p)$ as

$$-\left(\frac{\partial S}{\partial p}\right)_T = \left(\frac{\partial V}{\partial T}\right)_p. \tag{2.67}$$

In equilibrium, G is minimum.

If the system absorbs heat from the reservoir and performs work against the constant pressure of the reservoir quasistatically, the maximum work (*other* than the work done on the pressure reservoir) is given by the change of $G(T, p)$. This is the reason why G is called a "free energy."

Summary of Formal Aspects

Internal energy U, enthalpy H, entropy S, Helmholtz free energy F, and Gibbs free energy G characterize system *properties*. They are described by *state functions*.

Infinitesimal changes of state functions are total differentials. The integral of a total differential between an initial state 1 and a final state 2 is *independent* from the path of integration. Exergy, on the other hand, is *not* a state function of the system, because it depends not only on internal properties of the system but also on properties of the environment. The exergy of a system with internal energy U, entropy S, and volume V that is not in equilibrium with its environment of constant temperature T_0 and pressure p_0 is, according to (2.45), $E_X = (U - U_0) + p_0(V - V_0) - T_0(S - S_0)$. This can be written as the difference of two terms that formally resemble the Gibbs free energy. With the definition $G_0(U, S, V) \equiv U - T_0 S + p_0 V$, the exergy of the system relative to its environment becomes

$$E_X = G_0(U, S, V) - G_0(U_0, S_0, V_0). \tag{2.68}$$

Appendix 2: Energy Units

Magnitudes

Symbol	Abbreviation	Number	Word
μ	Micro	10^{-6}	
m	Milli	10^{-3}	
k	Kilo	10^{3}	Thousand
M	Mega	10^{6}	Million
G	Giga	10^{9}	Billion
T	Tera	10^{12}	Trillion
P	Peta	10^{15}	Quadrillion
E	Exa	10^{18}	Quintillian

SI Energy Units

SI is an abbreviation of *Système International* (French for “International System”).

One joule (J) = 1 watt second (W s)

1 megajoule	$= 10^6$ J	= 1 MJ
1 gigajoule	$= 10^9$ J	= 1 GJ
1 terajoule	$= 10^{12}$ J	= 1 TJ
1 petajoule	$= 10^{15}$ J	= 1 PJ
1 exajoule	$= 10^{18}$ J	= 1 EJ

One million (metric) tons of coal equivalents (tCE) =1 MtCE = 29.3 PJ
One million tons of oil equivalents (tOE) =1 MtOE = 41.9 PJ
One ton of oil equivalents = 7.3 barrels of oil equivalents (1 barrel = 159 liters)
Historical unit: calorie (cal); 1 cal = 4.19 J

Energy Conversion Factors

Units	MJ	kWh	tCE	tOE
1 MJ	1	0.278	0.000034	0.000024
1 kWh	3.6	1	0.000123	0.000086
1 tCE	29,304	8,140	1	0.700
1 tOE	41,868	11,630	1.429	1

Power Units

One watt (W) = 1 J/s
One horsepower (hp) = 0.7355 kW

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